MACHLETT **CATHODE PRESS**

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IN THIS ISSUE

Cover:

Machlett planar triodes serve the nation's commercial airlines for air traffic control in DME and Transponder equipment.

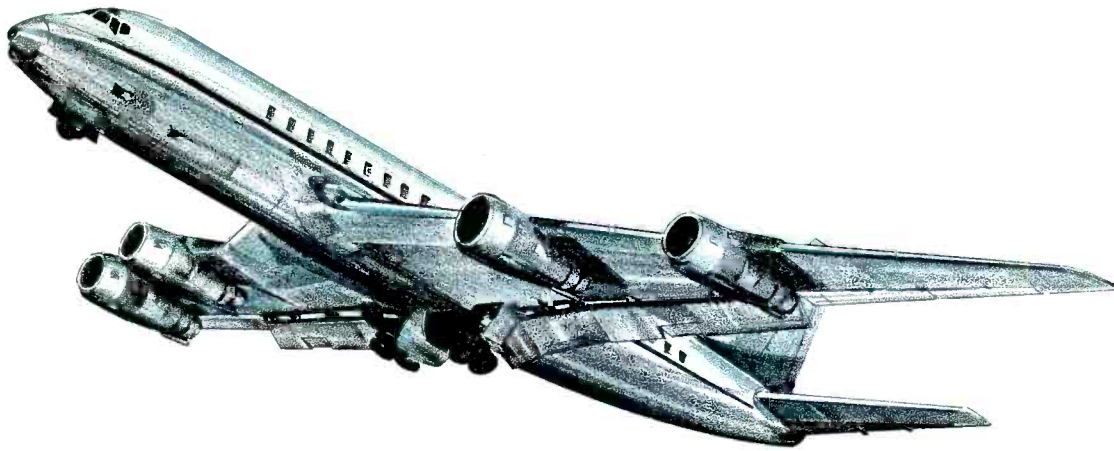*Product Lines represented in this issue:*

Small Power Tubes

Large Power Tubes

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MACHLETT

ELECTRON TUBE SPECIALIST

Introduction

In this and in the following issue Machlett Laboratories' position in the field of commercial aviation is reviewed by CATHODE PRESS. At a time when the use of solid state devices has become nearly universal in new airborne electronics equipment, and the use of electron tubes has diminished accordingly, the Machlett planar triode continues to maintain — even increase — the extent of its application. Today all airlines flying 4 engine equipment use the DME and Beacon Transponder. In each of these units one or more planar triodes is employed.

Machlett planar triodes (including the ML-7855, ML-7815 and ML-6442) are used by the great majority of carriers as the preferred tube type. This is so because the equipment manufacturers, as described in this issue, have found significant advantage in the Machlett offering.

The Machlett contribution lies not only in the reliability of its planar triode but in the new level of performance it has made possible. In the areas of high voltage stability, grid pulsing, frequency stability, cathode activity and tube life, Machlett tubes have demonstrated superiority.

CATHODE PRESS, Volume 21, No. 2, describes DME and transponder development as seen by the manufacturer. Volume 21, No. 3 will describe the use made of these important navigation aids by several major airlines.
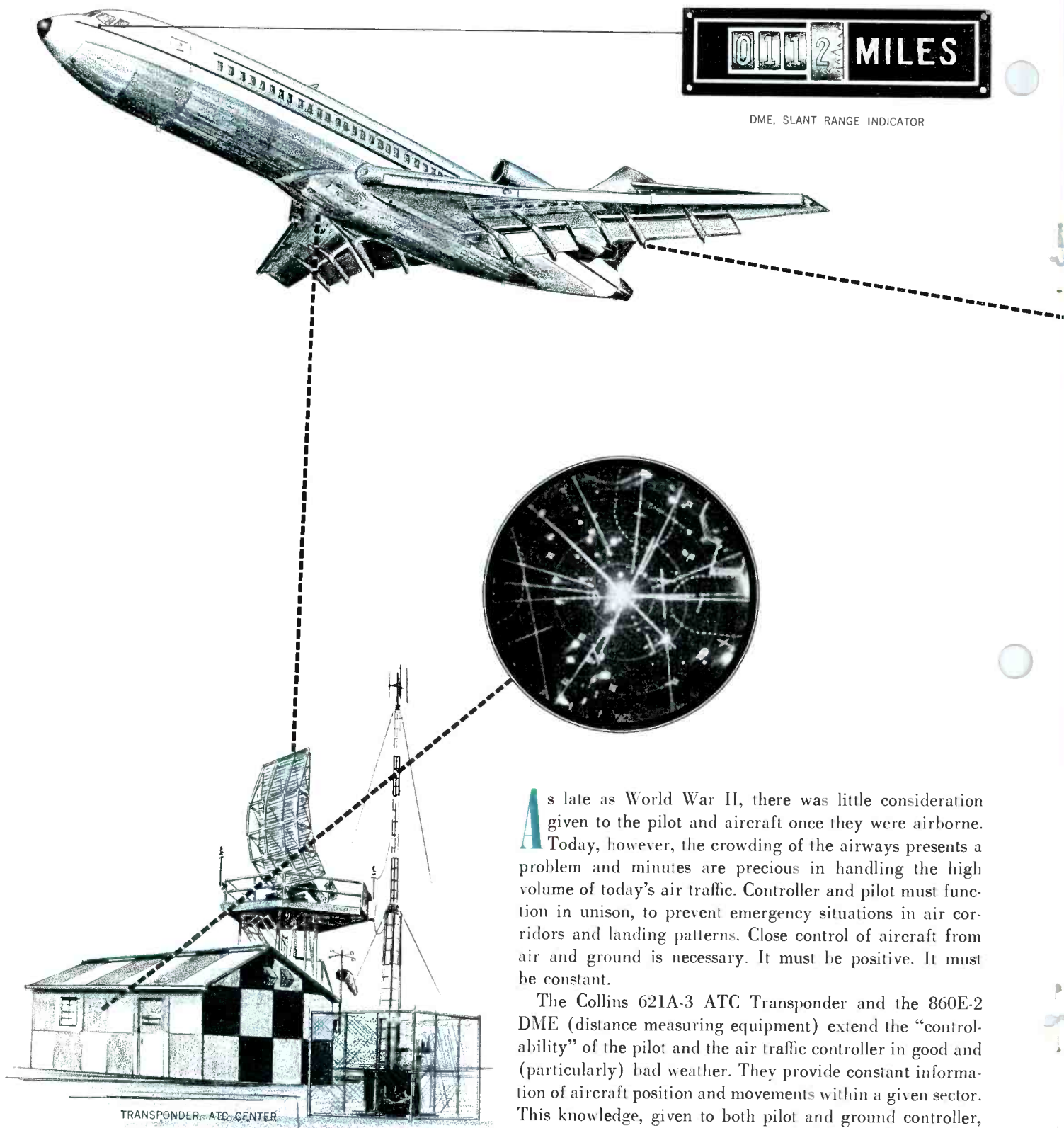
DME, SLANT RANGE INDICATOR

TRANSPONDER, ATC CENTER

Figure 1 — Better Air Service with Modern Electronic Aids.

As late as World War II, there was little consideration given to the pilot and aircraft once they were airborne. Today, however, the crowding of the airways presents a problem and minutes are precious in handling the high volume of today's air traffic. Controller and pilot must function in unison, to prevent emergency situations in air corridors and landing patterns. Close control of aircraft from air and ground is necessary. It must be positive. It must be constant.

The Collins 621A-3 ATC Transponder and the 860E-2 DME (distance measuring equipment) extend the "controlability" of the pilot and the air traffic controller in good and (particularly) bad weather. They provide constant information of aircraft position and movements within a given sector. This knowledge, given to both pilot and ground controller, greatly reduces the possibility of an air tragedy and increases the serviceability of an airline.
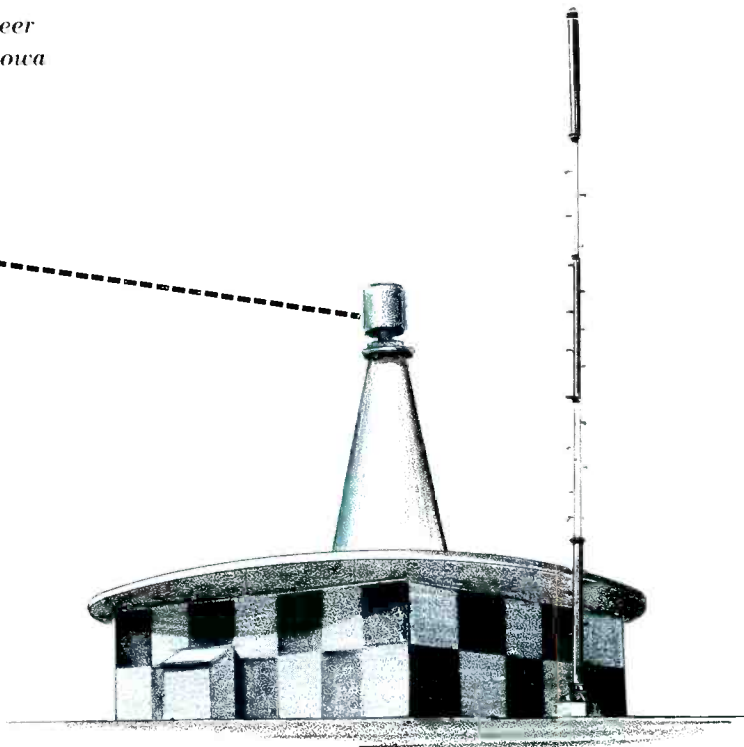
ATC Transponder for Controller

Transponders are used for establishing the azimuth and distance of an aircraft from an ATC center. This is done by

Positive Control from Air and Ground

By FRED EGGERT, Publications Engineer
Collins Radio Company, Cedar Rapids, Iowa

VORTAC STATION

transmitting a coded interrogation from the ground station. The ATC Transponder (Figure 2) equipped aircraft receives this interrogation and decodes it. That is, it determines that it is in fact an interrogation to a transponder. The ATC Transponder codes a reply to the interrogation which is then transmitted to the ground station. An active reply rather than an echo is used to eliminate problems with precipitation, clouds, and ground clutter and to extend radar range. The ground station decodes and displays the reply on a cathode ray tube screen. The face of this tube is overlaid with a map to show the location of the aircraft with respect to airways, navaids, and holding areas. Coding of a reply signal is used in ATC to identify particular operating conditions of aircraft. The codes are displayed on a digital readout, which indicates whether the aircraft is climbing, flying at a particular altitude, or descending.

An air traffic controller can follow the progression of aircraft through a given sector, using the cathode ray tube representation. With a glance, he can determine which aircraft are in the area and their relative positions. And, using voice communications, the ground controller can direct or

position the aircraft within the sector. Aircraft not equipped with a transponder are located using an echo-reply system and are integrated with those transponder equipped aircraft on the cathode ray tube screen. This gives the ground controller a complete air picture of all the aircraft in his sector.

Because transponder-equipped aircraft have the capability to provide the ATC controller with a continuous, positive indication of their position, it is possible for them to obtain clearances, which, if requested by non-transponder aircraft, would be either delayed or denied.

In planning flights, for example, it is often advantageous to go direct rather than to follow a series of airways which dog leg back and forth. Under IFR (instrument flight rules) conditions where there is extensive traffic, controllers are reluctant to grant direct clearances to non-transponder aircraft because of difficulty involved in providing separation of aircraft paralleling and crossing airways and going as long as 30 or 40 minutes between positive fixes.

A transponder-equipped aircraft, however, because it is continuously fixed on the controller's scope, can be easily integrated with the airway traffic in the area. As a result,

transponder equipped aircraft generally obtain clearances more quickly and experience fewer changes of flight plan and delays enroute.

In high density areas aircraft not equipped with a transponder are required to report over a definite fix and to make identifying turns as prescribed by the controller so that they can be positively identified. Only then can they be worked into the approach pattern. If, because of precipitation or ground clutter, the controller loses the target for any length of time, it may be necessary for the aircraft to once again be identified by executing a series of turns.

The transponder equipped aircraft, by way of contrast, is positively identified as soon as it appears on the approach controller's scope and is often vectored directly into the approach pattern, thereby saving a considerable amount of time.

If a situation should occur, either enroute or in a terminal area, that would require an immediate descent and landing, the transponder equipped aircraft can be quickly cleared and vectored to the nearest suitable field. Even if all VHF communications are lost, with an aircraft in distress, the transponder permits it to be quickly identified by transmitting the emergency pulse code. The other aircraft in the area could then be vectored so as not to conflict with the distressed aircraft.

The 621A-3 ATC Transponder

In addition to all of the attributes noted for transponders, in general, the Collins Radio Company 621A-3 ATC Transponder incorporates several new features. Completely solid state except for the transmitter tube, the 621A-3 incorporates both two and three pulse sidelobe suppression, an expanded reply code system of 4096 combinations, and all the circuits required for automatic altitude reporting. Space has also been reserved for the addition of such other functions, such as automatic selective reply on all modes, that may be required in the future. Also, a self-test feature is available which can be operated by a switch on the front panel of the radio and remotely by a switch on the control panel. This provision can be used to interrogate the transponder and check the reply to assure that the transponder is operating properly. The circuit gives a visual and aural indication of the transponder operation. This self-test check extends from the input of the receiver to the output of the transmitter. Receiver sensitivity, decoder performance, and transmitter power output can be checked on the ground or in flight using this feature.

The three-pulse sidelobe suppression system provides for an interrogation containing three pulses. The secondary surveillance radar (SSR) station transmits 0.8 microsecond wide pulse pair interrogations (P1 and P3) from the directional rotating antenna. Pulse spacing between P1 and P3 is determined by the mode of operation. Two microseconds after the initial interrogation pulse (P1) is transmitted, the

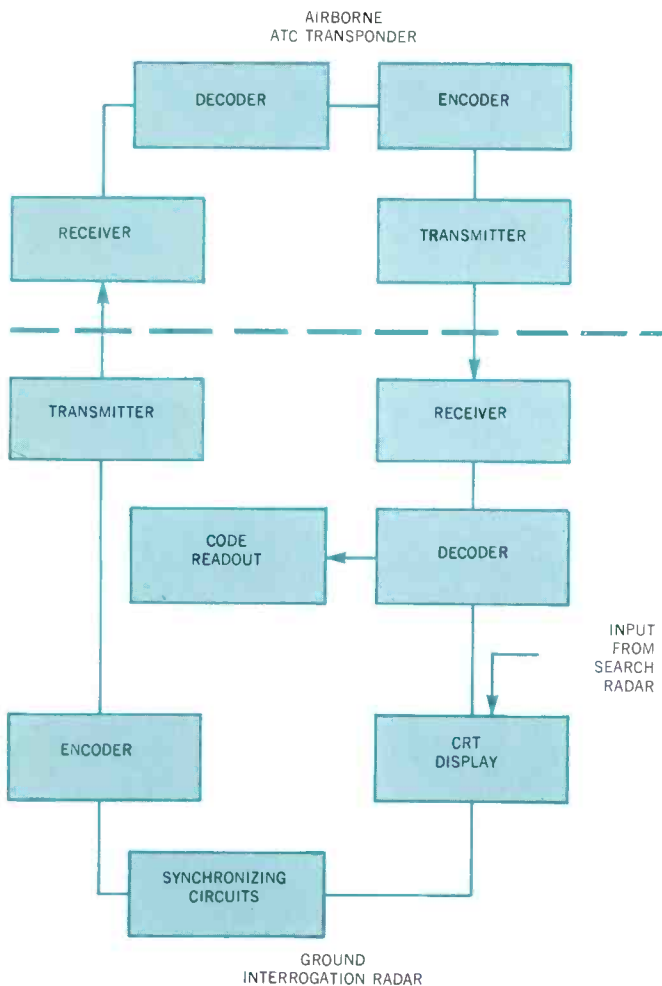Figure 2 — ATC Transponder System, Block Diagram.

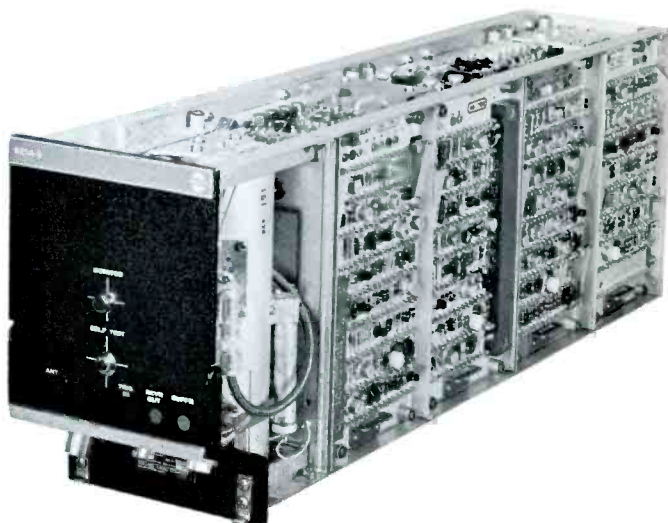Figure 3 — ATC Transponder, Dust Cover Removed.

Figure 4 — Decoder Module.

two pulse system. The first pulse (P1) is transmitted by the omnidirectional antenna. The last pulse (P3) is transmitted by the directional rotating antenna and is used, in amplitude comparison with P1, to determine whether or not the interrogation is valid. The two-pulse method of interrogation is presently used in Britain. The two-pulse sidelobe suppression circuit is an optional feature of the 621A-3.
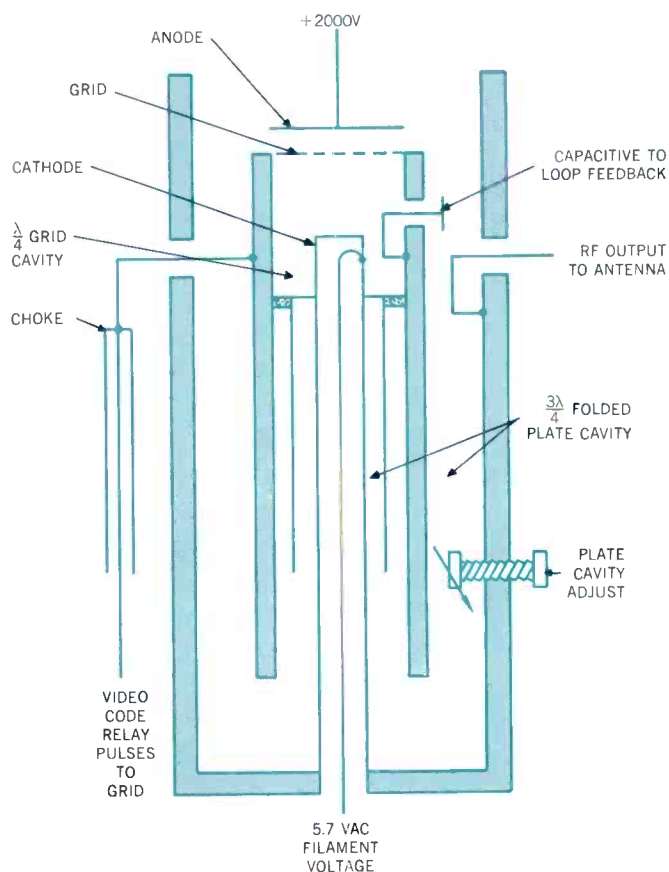
RF Cavities

The 621A-3 uses a Machlett ML-7815 mounted in a ¾ wave "double folded back" cavity. The ¾ wave cavity results in a higher Q with the cavity loaded. The high Q provides increased stability for the transmitter frequency. However, the higher Q also requires a tube having greater power capability.

Grid pulse modulation techniques, for the transmitter tube, allow use of a transistorized modulator and eliminate the

Figure 5 — Tube Equivalent Circuit.
For the 621A-3 ATC Transponder, the mounted ML-7815 employs two cavities, one fixed ¼ wavelength cavity in the grid and the second a variable ¾ wavelength cavity in the plate circuit. The capacitance of the plate tank is variable to allow adjusting of the output frequency. Feedback, to sustain oscillations in the circuit, is provided through capacitive-plate to inductive-loop coupling in the grid circuit. The output rf pulse is inductively coupled out of the ¾ wave "double folded back" plate cavity to the antenna.

Figure 5 — Transmitter (with ML-7815) Equivalent Circuit.

omnidirectional antenna, located with the SSR, transmits a 0.8-microsecond-wide reference pulse (P2) for sidelobe suppression. The P2 pulse is used, in amplitude comparison with P1, to determine whether or not the interrogation is valid. A two-pulse interrogation in a three-pulse circuit is always accepted as a valid interrogation. The three-pulse method of interrogation is used in the U.S. and Canada. It is anticipated that the three pulse system will be universal in a few years.

The two-pulse method of sidelobe suppression provides for an interrogation containing only two pulses. The SSR station transmits a pulse pair interrogation that utilizes a rotating directional antenna and fixed omnidirectional antenna radiations. Pulse spacing between P1 and P3 is determined by the mode of operation. There is no P2 pulse in the

Figure 6 — Transmitter Tube Drawing.

(Figure labels: FOLDED GRID INPUT CHOKE; TRANSMITTER TUBE; $\frac{3\lambda}{4}$ FOLDED PLATE CAVITY; $\frac{\lambda}{4}$ GRID CAVITY)
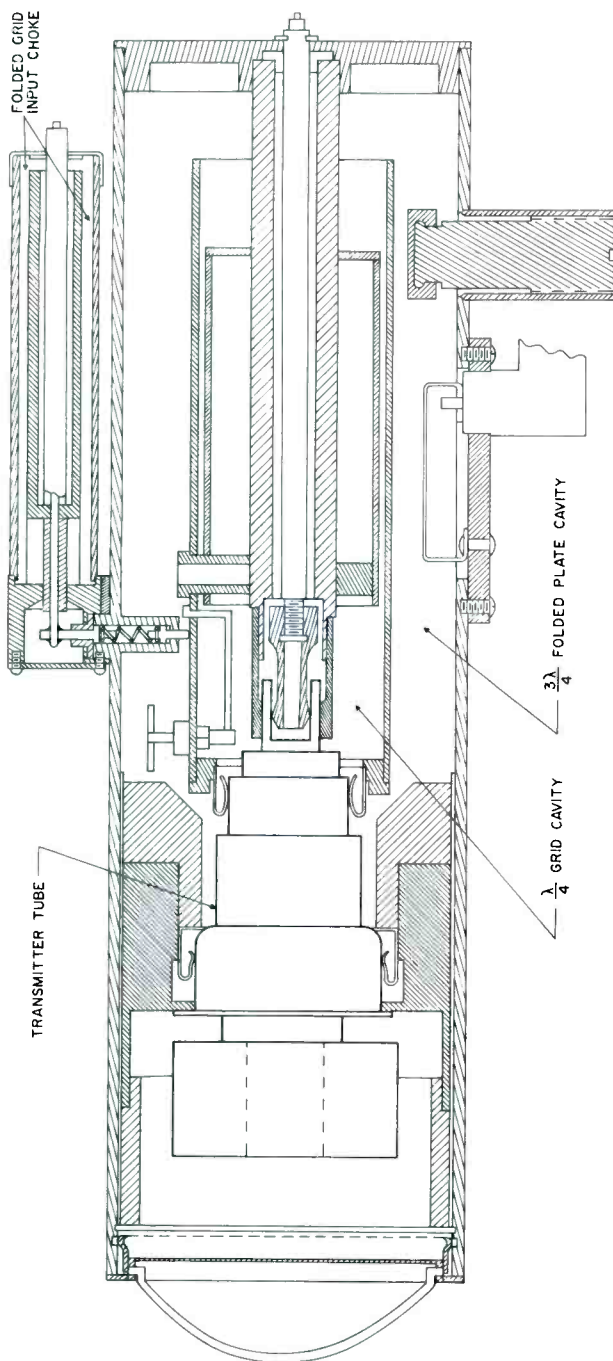
For several years planar transmitting tubes similar to the 2C39 have been used in airborne navigational equipment. New and more stringent requirements have caused continued tube research and improvement. Machlett's research has resulted in the development of the ML-7815. Utilizing the modern Phormat Cathode, the ML-7815 is capable of higher dc plate voltages without destroying the cathode coating. Collins Radio Company selected the ML-7815 as meeting the reliability requirements necessary for the 621A-3 ATC Transponder and the 860E-2 DME.

need for an elaborate plate pulsing power supply. The tube used in this type of equipment must be extremely reliable and have a long life expectancy. The Machlett planar triode ML-7815 was selected for these qualities.

DME

Perhaps the greatest single advance in achieving air navigational safety and efficient air traffic control was taken by the mandatory addition of DME (Distance Measuring Equipment) to commercial air navigation. A focal point of close observation in 1960, DME was given Air Transport of America sanction in a conference held January 19, 1961. The members of the Special Airlines Operations Conference, held in Chicago, determined then that aircraft operated by commercial carriers must have DME.

The action of this committee was justified, and it has been subsequently proven that the airways have been made safer through the use of DME; in addition, the airlines have found DME to be a money saving device. Some of the safety-money-time savings aspects of the DME include:

1. A more precise location of checkpoints than is possible using the intersection of two VOR radials.
2. Allows the pilot to report the exact location of storm cells, when used with weather radar.
3. DME allows approximately a 5 to 1 reduction in enroute separation standards used by ATC.
4. DME allows approximately a 4 to 1 reduction in separation between aircraft departing from a terminal area.
5. Allows back-course ILS let-downs under low ceilings when accurate distance information can effectively replace the glide slope information.
6. Permits quick accurate computation of upper winds.
7. Eliminates procedural turns in some ILS approaches.
8. Better holding patterns.
9. Instant positive position indication (when used with a VOR system).

DME is an active tool of the pilot and a passive tool of the ground controller. The pilot has constant reference to this tool and, since the ground controller is aware of this, the controller can give directions using this active tool as a reference. An example of this is through the use of holding patterns. Previously, holding patterns were established through the use of either time flights or land mark references. The ground controller would for example direct the pilot to fly in one direction for three minutes, turn, then fly in the opposite direction for three minutes. If the day was clear the pilot could be directed to fly to a particular land mark, turn and fly to another land mark and to hold that pattern until told to land.

These methods were, at best, poor. The visual (land mark) method depends on a clear day and the number of such land marks available. And, the proper spacing of land marks is definitely a limiting factor. Flying for a certain number of minutes in a specified direction is problematic
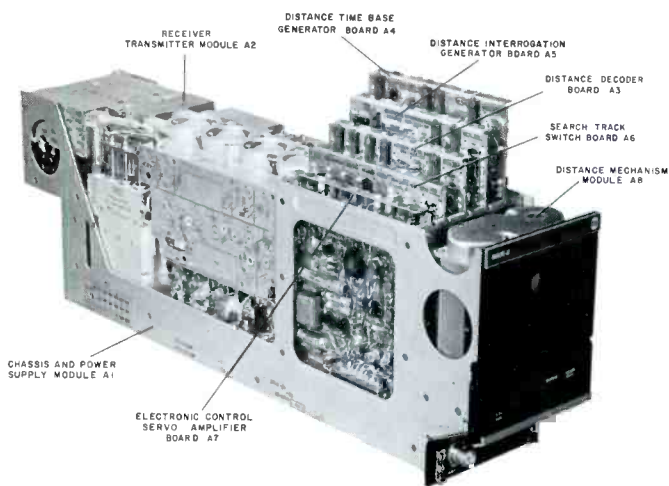
Figure 7 — DME with Dust Cover Removed.

from the aspect of aircraft speed deviation. A jet aircraft will fly more miles than a piston aircraft will, over a given amount of time. Airspace is, therefore, not controlled when these two holding methods are used.

Using DME with a VOR equipped aircraft, the controller can designate the exact distances the aircraft may fly from the VOR and the VOR radial that may be used. Using the DME the pilot can hold this prescribed air pattern. By using this tighter control device, the aircraft becomes safer and safety is essential.

Prior to the requirement for DME, pilots were asked their opinion of the ATC probems; their replies supported the need for DME. One pilot remarked: "ATC procedures in high density areas are woefully inadequate and if DME is the missing link it is badly needed." Since that time in early 1961, DME has proved itself.

DME, How It Works

The distance measuring operation begins when the transmitter portion of the 860E-2 DME transmits a pair of interrogation pulses. These interrogation pulses are received by the selected TACAN or VORTAC ground station. The ground station, after a fixed time delay, transmits a pair of reply pulses. The fixed delay time is used to standardize the inherent delay in every piece of electronic equipment. These reply pulses are received and detected in the receiver portion of the 860E-2 DME and applied to the computing circuits. The computing circuits measure the time interval between the transmission of the interrogation pulses and the reception of the reply pulses. The time interval, which is proportional to the slant distance between the aircraft and the ground station, is converted to distance information for display on the DME distance indicator.
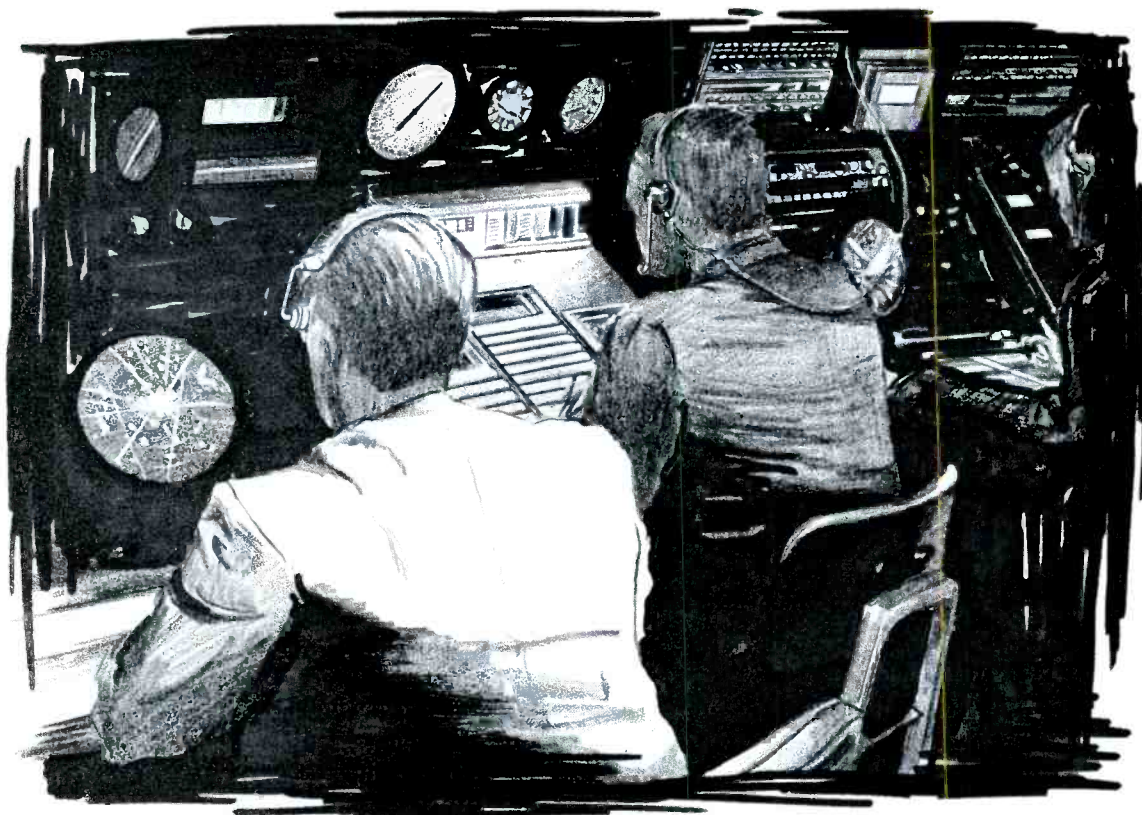
The DME ground station, called a VORTAC station, consists of a TACAN station and a VOR transmitter. The VOR transmitter provides bearing information to aircraft equipped with VOR receivers. A TACAN ground station has the capabilities to reply to DME interrogation signals and also to transmit bearing information and identification signals. The bearing information consists of amplitude-modulated pulses and is used mainly by the military as a source of bearing data.

The 860E-2 DME

The 860E-2 has several new and important features. With the exception of five tubes, the circuits of the DME are completely solid state. Solid state components require less space and weigh less. Consequently, Collins was able to add additional circuits with new functions and refine existing DME circuits. Solid state components require less cooling (no filaments), less power, and extend the reliability of the system. Four of the tubes used are the rf power amplifiers. These amplifiers are Machlett ML-7815 planar triodes and are operated at a very conservative level which extends the operating time. Life tests run with the ML-7815 have produced rather interesting results. The tubes were placed in test fixtures using the general circuit configuration of the 860E-2. The tubes have run over 3000 hours so far with no measurable change in the tube characteristics.

The memory circuit used in the 860E-2 permits the user to select either a velocity or static memory for the system by movement of internal jumper wires. With the velocity memory, and when track is lost, the distance indicator continues to track a synthetic signal at the same rate as the original signal before loss. With static memory, the distance indicator is locked on the same point during memory at the last distance displayed before the signal was lost.

Obsolescence of the 860E-2 is minimized through the use of such features as the built-in split channel circuit. Present DME channel requirements are satisfied by the use of 126 channels. Because of the ever increasing use of air transportation, however, DME ground facility density will increase for a given area. Therefore, by simply changing a jumper wire in the 860E-2, accommodation is made for 252 channels. No other circuit modification is necessary.

RF Cavities of the 860E-2

The 860E-2 rf cavities consist of four plate pulsed amplifiers in cascade. Low level cw rf is supplied to the input circuit of the first amplifier. When the high voltage pulse is supplied to the anode of the amplifier, the applied cw is amplified. The pulsed output is amplified in sequence by the following three plate pulsed amplifiers. Each successive stage

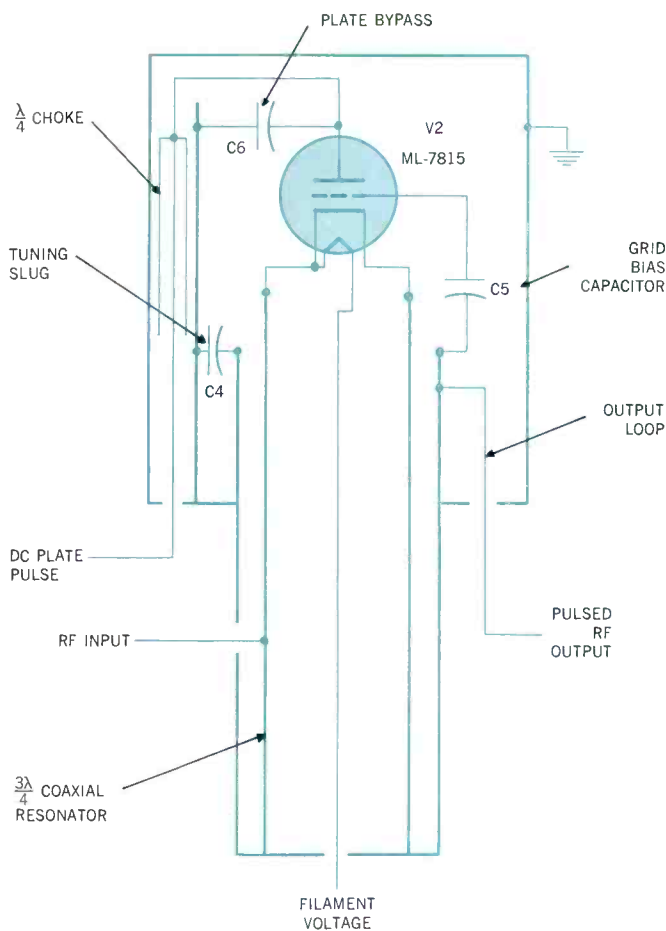Figure 8 — DME System Block Diagram.

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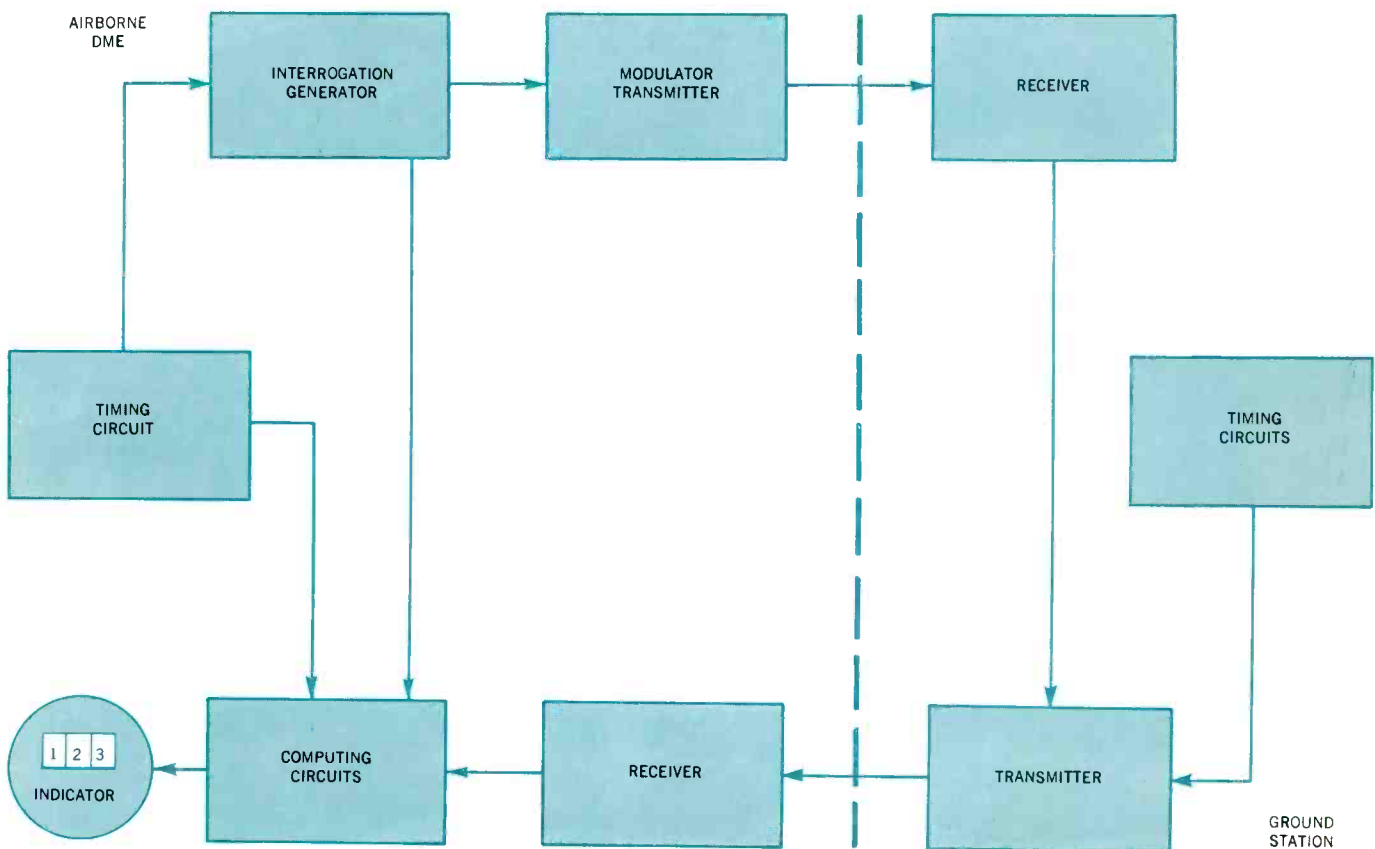
Figure 9 — ML-7815 Cavity High Frequency Equivalent Circuit.

increases the amplitude of the pulsed rf to the output stage. Collins has designed this circuit so that when the cavity tuning is peaked the output power will be approximately 2000 watts. This allows a 3 db margin over the published output power rating of 1000 watts, to accommodate tracking errors and provide for tube aging.

A ¾ wavelength coaxial line section (Figure 9) is used at the input of each amplifier. The coaxial section provides impedance matching and rf isolation for the filament circuit. The grid current caused by the rf is rectified by the cathode-to-grid action charging grid capacitor C11. This charge provides the grid bias for the ML-7815. The output circuit is a ¼ wave coaxial resonator. The output is tuned by adjusting C10. Capacitor C10 consists of the capacitance between the inner and outer conductors of the resonator as provided by the tuning slug. The resonant frequency of the output coaxial resonator is varied by the axial position of the tuning slug.

The plate supply voltage is applied through a quarter wave choke to the ML-7815 anode. The quarter wave choke reflects an open circuit to rf. Consequently, rf isolation to the anode supply is adequately provided, and rf radiation from the anode lead is kept to a very low level.

•   •   •

Through the evolution of improved techniques in tube design and processing, Machlett Laboratories maintains pace with the requirements of the air industry by consistent dependable quality. This is evidenced by the development of the ML-7815, which is standard for both the Collins Radio Company 860E-2 DME and the 621A-3 ATC Transponder.
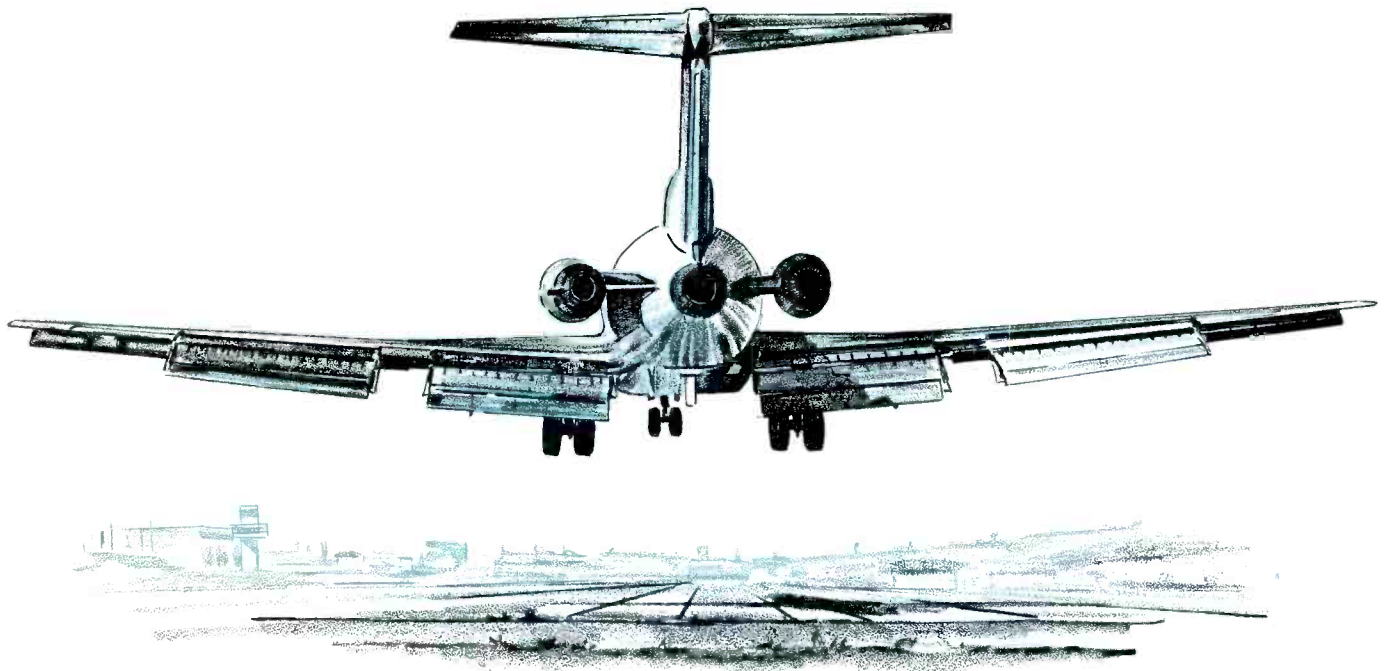
A Co-incident Evolution: Avionics and

By
HENRY EGGERDING,
Senior Project Engineer
Commercial Avionics
ITT Federal Laboratories
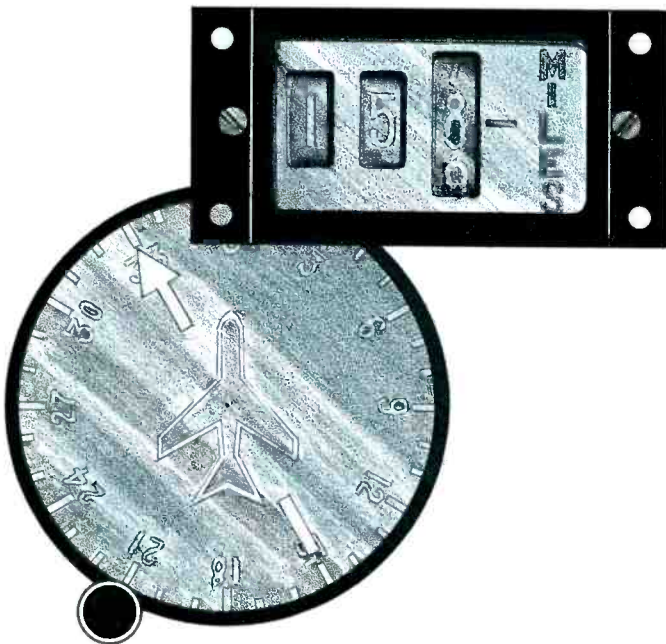
The Planar Triode

Today's air traffic control system requires accurate aircraft position reporting and planning to provide the air travel safety margin we have come to expect. The need for system improvements and the tightening of accuracy tolerances evolves from increasing air traffic density, high speed jet aircraft operation and even higher speed supersonic transport programming.

Aircraft position is determined by three parameters:

    (a) Altitude.

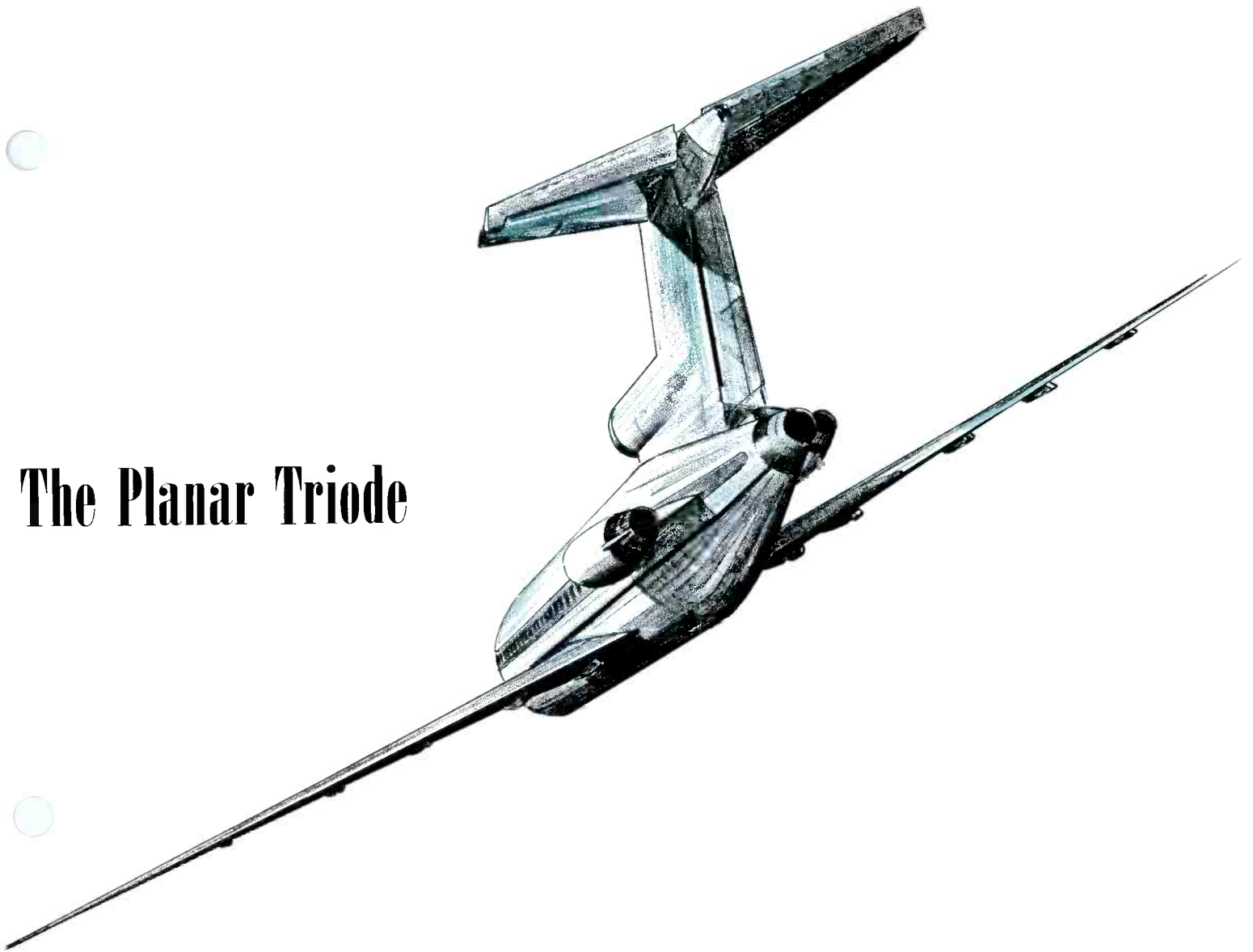   (b) Flight track azimuth with reference to a fixed geographic location.

    (c) Distance from a fixed geographic location.

The pressure or barometric altimeter provides the first of these parameters reasonably satisfactorily and is used to establish and maintain flight levels for ATC purposes. If a common geographic location is used for (b) and (c) above, we have the elements of a polar coordinate navigation system and it is upon this rho-theta concept that the most widely accepted modern, short range navigation systems are based. (See Figure 1). Since the three broad classes of aircraft, namely general aviation, airline, and military share the same airspace, it is almost essential that a common system giving rho-theta information be available to these users.

As a matter of interesting history, the four course low frequency A/N range system came into use in 1929. In spite of its limitations of only four flight tracks and severe static interference susceptibility, due to its frequency range of 200 to 400 kc's, it served well for many years, but is now obsolete.

The VOR (VHF Omnidirectional Range) which replaced it, gives an unlimited number of flight tracks over 360°. In its frequency range of 108 to 118 mc, it is essentially static free, and it provides precision visual guidance and aural identification in contrast to the purely aural guidance of the A/N range.

These systems provide flight tracks, but no direct information of position along the track. As a matter of fact, the majority of any pilot's cockpit time for the past two decades has been devoted to resolving aircraft position, or establishing the rho element in the purely "theta" systems that have been available to him.
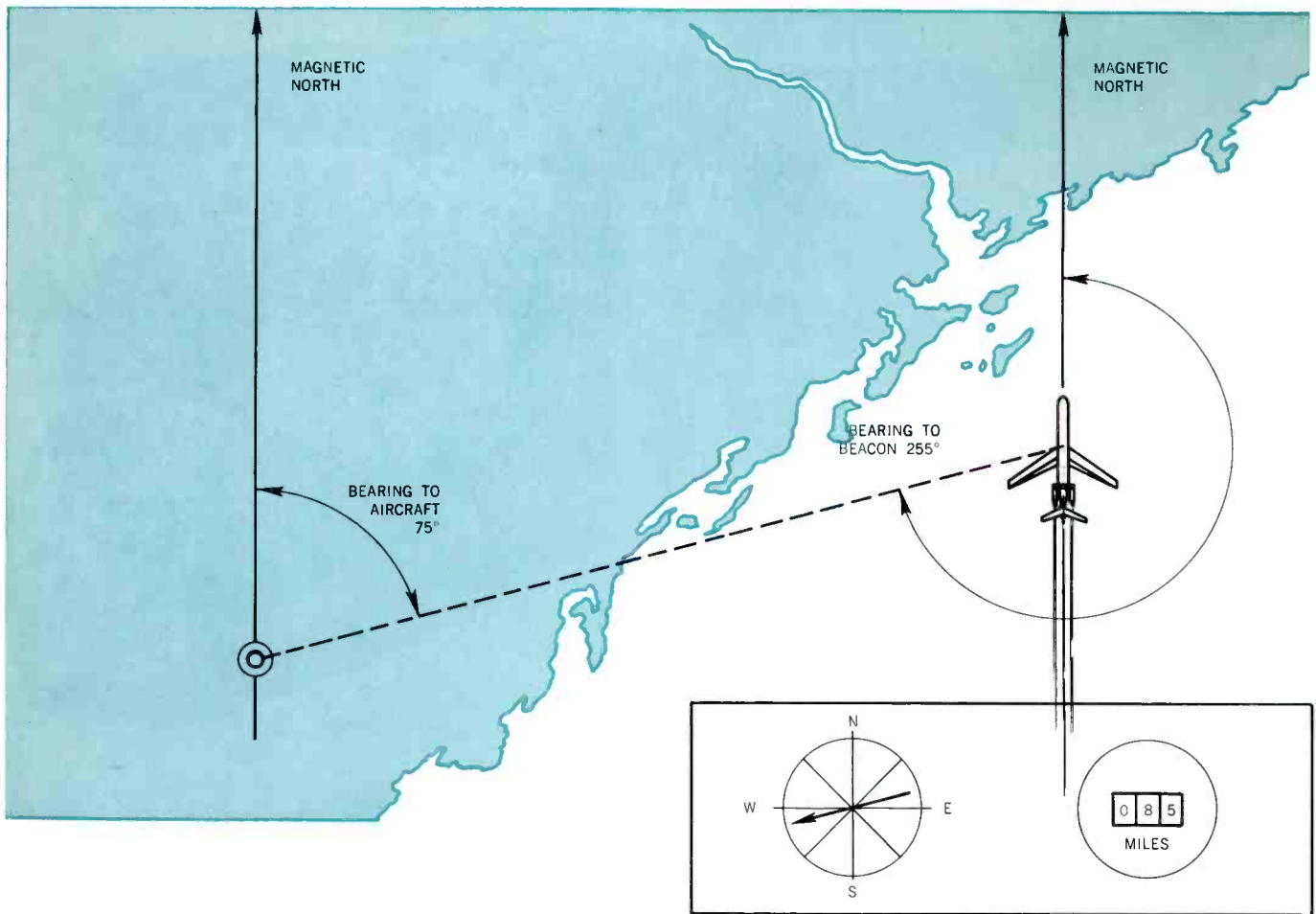
Figure 1 — RHO-THETA Diagram.

The Development of DME

Radar was widely used in WWII to get direct, accurate, distance information, but the method was a cumbersome one calling for a radar operator, a cathode-ray display, and considerable manipulation. It was obvious to many that if this method could be automated and if the cathode-ray display could be eliminated, we could have a pilot-operated system which would give continuous information of progress along the flight track. The outcome was the system we know today as DME (Distance Measuring Equipment).

DME employs a pulse coding technique whereby an airborne transmitter-receiver in the 960 to 1215 mc band, "interrogates" the ground station which is co-located with the azimuth portion of the system, the VOR station. The DME ground station decodes and replies to the interrogator. Since the airborne unit measures the time interval between its interrogation and receipt of the ground station reply, "miles" can be displayed for pilot use.

The combination of VOR and DME gave a rho-theta system which well filled the needs of non-military users. However, various difficulties in military deployment and utilization prevented it from becoming the common military-civil system. Unique military requirements led ITT Federal Laboratories* to conceive and develop the 126 channel integrated distance/bearing system, known as TACAN (Tactical Aerial Navigation). This pulse coded system also in the 960 to 1215 mc band proved so successful that it received world-wide acceptance and resulted in new industry business in hundreds of millions of dollars. Today some 30 prime TACAN manufacturers and countless suppliers participate in this new business.

VORTAC

The need for co-location of the rho-theta ground stations lead to a system known as VORTAC in which the VOR and TACAN ground stations were co-sited and the military/civil common system was made available. Civil aircraft now use the DME portion of TACAN for distance and the VOR for azimuth, while the military aircraft use full TACAN for both distance and azimuth.

Expansion of the VORTAC DME to provide 252 channels

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*ITT Federal Laboratories, Nutley, N.J., is a Division of International Telephone and Telegraph Corporation.

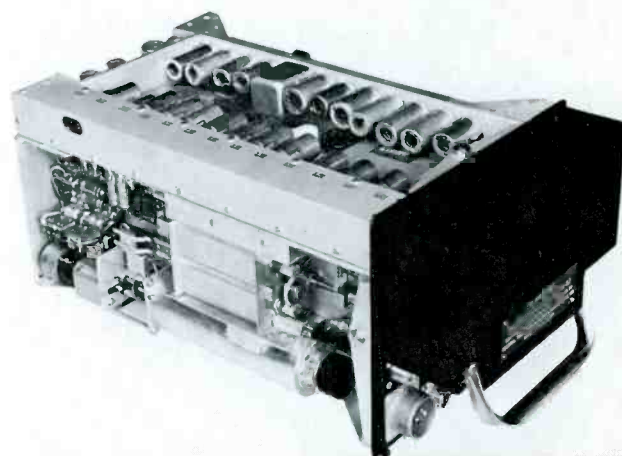Figure 2 — AN/APN-34 DME overall view with accessories.

Figure 3 — AN/APN-34 DME without dust cover showing 2C39A oscillator.

Figure 4 — DIA DME overall view with accessories.

Figure 5 — DIA DME without dust cover showing upper portion.

and expansion of TACAN to provide air-to-air Distance/Bearing service is on the immediate horizon. In fact, currently delivered ITT DME-100B's contain the feature of 252 channels (Channel Doubling), while ITT's TACAN now being produced for the Navy, provides the additional feature of air-to-air DME.

Use of DME with ILS (Instrument Landing System) to provide continuous distance to touch-down is an obvious forward step. When a suitable radio altimeter and an automatic throttle control are added, a Low Approach/Auto-Land system will enable landings with lower ceiling and visibility minimums than are currently used. Such a system is now being airline evaluated, using the ITT ALT-200 Low Range Altimeter (1964).

These cockpit rho-theta systems afford the pilot precision navigation which in turn permits better en-route and terminal area traffic control. The end result of all this efficiency improvement is a considerable savings in fuel costs and

better on-time performance, both on arrival and departure.

It is interesting to note that the foregoing systems depend heavily on pilot position reports, and this can place considerable burden on the communications channels. Of special concern is the terminal area transition which is to the overall traffic control picture what the boundary conditions represent to an engineering problem. Whereas the rho-theta solution handles the en-route or steady state portion of the air traffic control problem fully, the need for more frequent two-way communication in the terminal area calls for a complementary semi-automatic solution.

The development of the air traffic control transponder system permits wholesale or selective aircraft interrogation and visual identification by traffic control personnel. As it is presently used, pulse coding permits ready identification of individual or of groups of aircraft without requiring voice communications. Through the ultimate use of altitude encoders, position-in-space can be readily established.
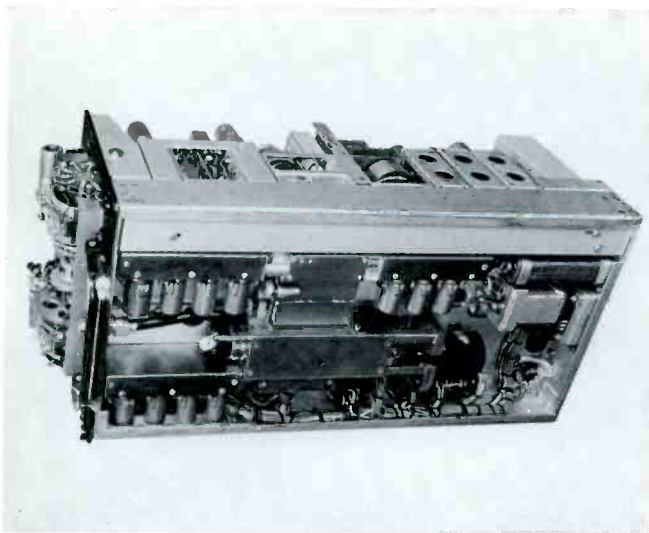
Figure 6 — DIA DME underside showing 2C39A oscillator.

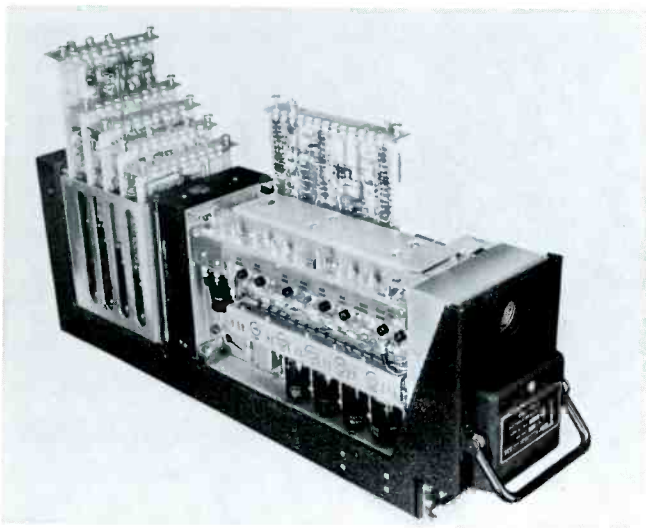Figure 7 — AFN-3544 airline DME prototype with accessories.

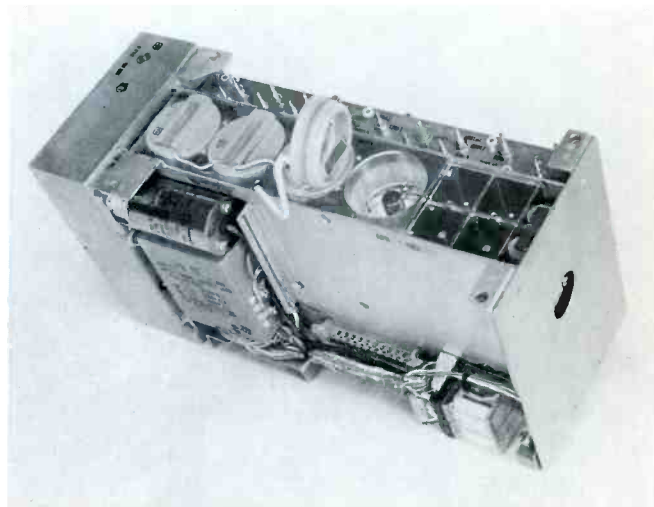Figure 8 — DME-100A airline DME semi-exploded view.

Figure 9 — DME-100A RF Module showing ML-7815.

These two systems are mutually independent and serve to provide the elements of a fully automatic ATC picture.

DME/ATC Transponder Similarities and Differences

The ATC transponder system is an outgrowth of the military IFF system in which an IFF Interrogator is co-located with a Search (Surveillance) Radar. The Interrogator antenna scans with the radar and when transponder equipped targets are "illuminated" by the pulse-coded interrogation, the targets reply on a different frequency (IFF/ATC transponder RF channels, one for each path, share the 950 to 1250 mc band with TACAN, but different pulse codes are used) with a signal which gives target identity, which can consist of a multiplicity of information bits including altitude, trip number and sequence.

Since the DME process starts and ends in the aircraft, the resultant information is immediately and continuously available in the aircraft while in the IFF/ATC case, the process is reversed and the information is present at the radar site. It must now, be relayed "manually" or "orally" to the aircraft to be of use to the pilot. IFF/ATC replies are usually presented on the radar PPI scope and here we have another difference between DME and IFF. It is highly desirable that transponder power output be held within close limits regardless of duty cycle, so that equi-strength signals (for a given range) are available at the output of the Interrogator's receiver and thus, that replies are of equal intensity when seen on the PPI display. DME signals in contrast are amplitude limited before processing to extract the time information so that transmitter power output is of little consequence.
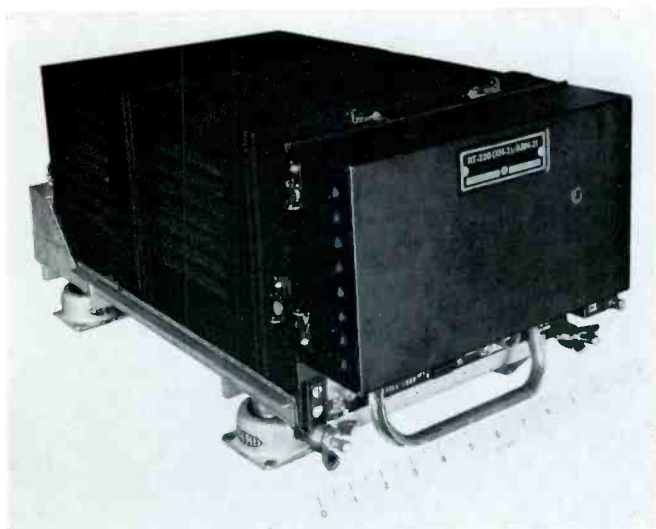
Figure 11 — AN/ARN-21 TACAN in dust cover, on shockmount.

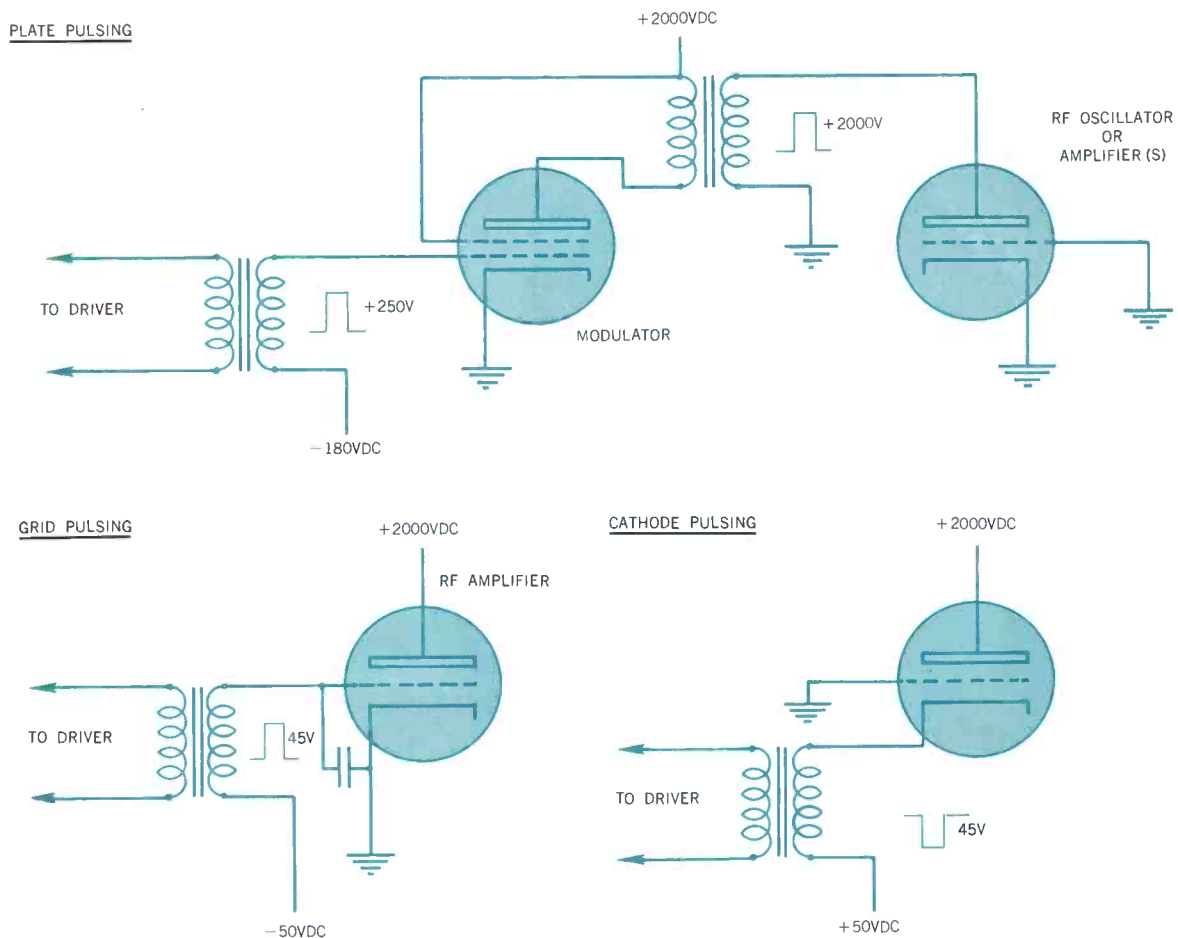Figure 10 — AIN-102A Distance Indicator for DME-100.

Figure 12 — Modulation methods.

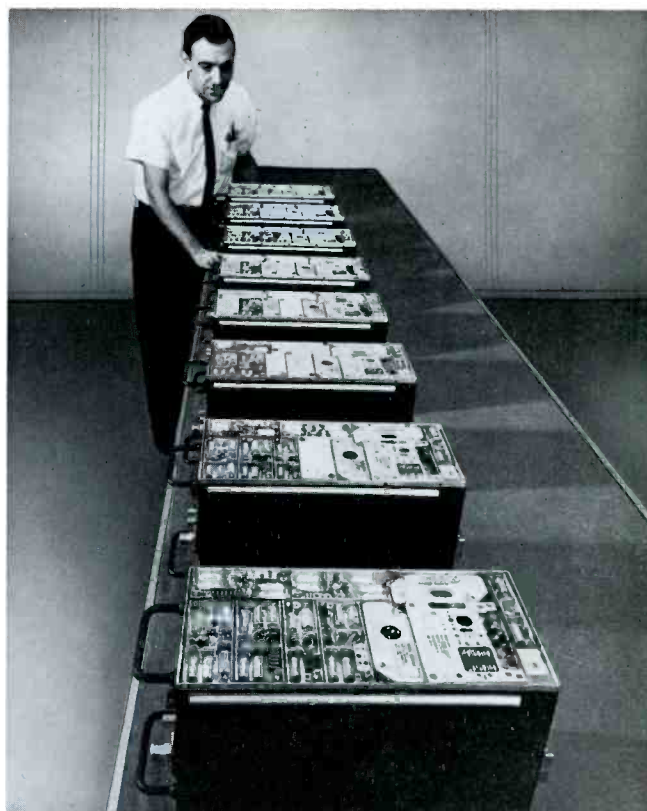Figure 13 — AFN-125, F-104 TACAN configuration with dust cover.

Figure 14 — Latest TACAN units.

In parallel with the evolution of radio navigation aids, an interesting evolution has taken place in the 2C39 planar triode. This glass envelope, external anode tube was designed in the early 1940's as a 100 watt plate dissipation, cw, transmitting tube. In early DME's designed and produced by ITT, it was used as a plate-pulsed oscillator with crystal-referenced AFC. The light DME duty cycle held plate dissipation well below 10 watts, although pulse voltages of between 2 and 3 kilovolts were applied to get power output in the kilowatt region.

TACAN to DME — Design Developments

The first airborne TACAN, the AN/ARN-21 (Sept. 1952) (Figure 11) designed and produced by ITT used a chain of five 2C39A's, again plate pulsed, in a direct crystal multiplier transmitter. (ITT's AN/APX-7, 1952, 1953, used a similar chain). It proved relatively easy to provide enough plate power from the modulator for the single 2C39 pulsed oscillators in the early DME's, but the multi-tube chains (in some cases the multiplier preceding the cascaded 2C39's was also pulsed) in the ARN-21 and the APX-7 required so much modulator power that modulator life was short when a tube of practical size was used. Loss of cathode emission was the predominant failure mode.

Grid Pulsed DME

This modulator tube life problem led ITT to seek a solution when design of the AFN-3544 DME was started late in 1956. In the type of plate pulsing circuit which we had used, a video tetrode with high plate and screen voltages was provided with cut-off bias. When the grid was pulsed "on" by the driver stage, the tetrode's cathode current became plate current for the RF stages. Since the tetrode's cathode emission capacity over a period of time was the limiting factor and since the cathodes of the RF tubes had a large emission capability, therein lay a possible solution. The tetrode was eliminated, its dc plate supply was connected to the RF tube anodes and cut-off bias was applied to the RF tube grids (or to the cathodes in later versions). The former tetrode driver was fed to the RF grids and we thus had "grid pulsing." (See Figure 12). A 5000 hour life test of this principle indicated that it was indeed a usable answer to the modulator problem in spite of the increase in transmitter cavity complexity and cost to allow for the application of the hold-off bias and the turn-on pulse to the RF tubes.

The ceramic 2C39B had appeared by this time and a

16

special version of this tube (the 3CPN10A5), with a finger-grip in place of the unused cooling fins and an extended grid/anode envelope was generated. Later, field experience showed that an emission-life-problem still existed with some of the 3CPN10A5's. Machlett's Phormat cathode came as a timely solution and led to the 7815 incorporating this feature.

ITT's AFN-125, F-104 configuration, Figure 13 (1960) which followed the AFN-3544 DME (1958) was required to provide more output power over a wider environmental range so the 7698, a high perveance version of the 7815, was developed by Machlett and of course, the Phormat cathode was included in this type also.

The new airline DME-100B, (1963), solid state, except for the multiplier/transmitter, which followed the AFN-3544 DME as ITT's airline DME, again uses 7815's in the transmitter chain. (See Figure 14).

We have thus come from a fragile, heat sensitive, glass 2C39 with its superfluous, for our use, cooling fins and a limited altitude capability (the AN/ARN-21 and the AN/APX-7 cut power output in half, above 35,000 feet to avoid arc-overs) to the 7815 and 7698. These tubes have proven much more uniform and rugged with the absence of cooling fins allowing more compact cavities. The Phormat cathode makes a substantial contribution to the life expectancy of more than 2000 hours for these transmitting tubes in spite of the demands of grid pulsing.

The 2000 hours life figure mentioned above is a significant factor in scheduled airline operation where premature failures result in spare equipment needs at remote locations, where in some instances, airline-owned radio repair facilities are non-existent. The spare equipment provisioning costs materially influence the equipment "buy" decisions since airline operating costs are materially affected by an equipment's mean-time-between-failures (MTBF).

Thus the equipment supplier shares a very important responsibility with the tube manufacturer in ever working towards better MTBF's — better still, lower customer costs. Transcending even this important factor is the continually increasing need for high reliability in an air safety environment.
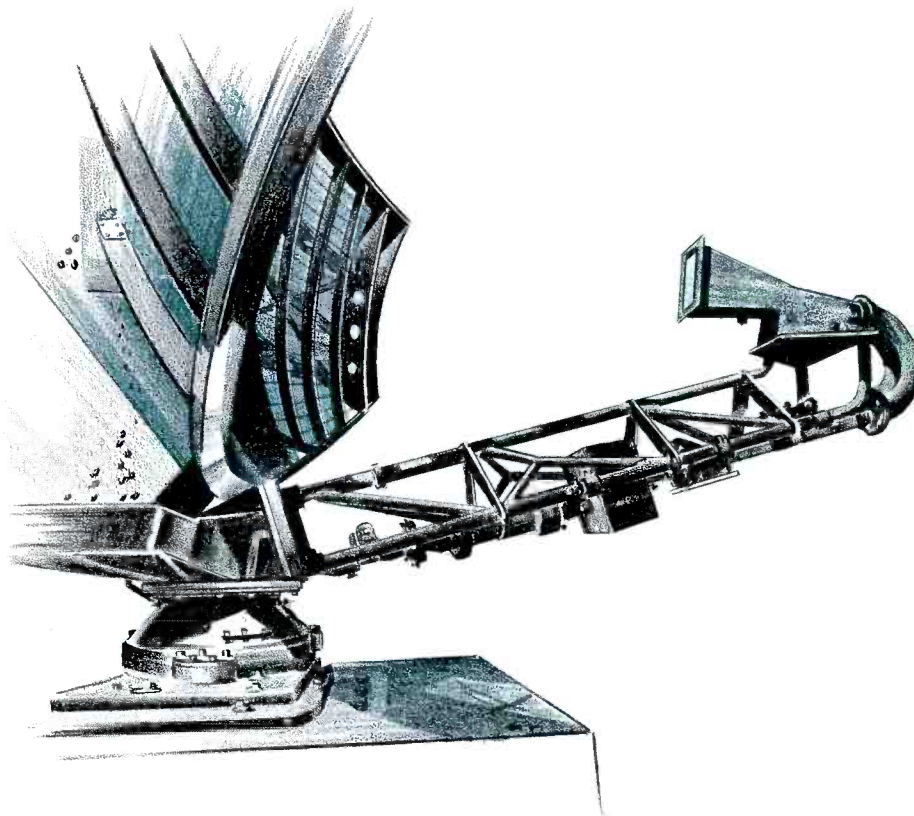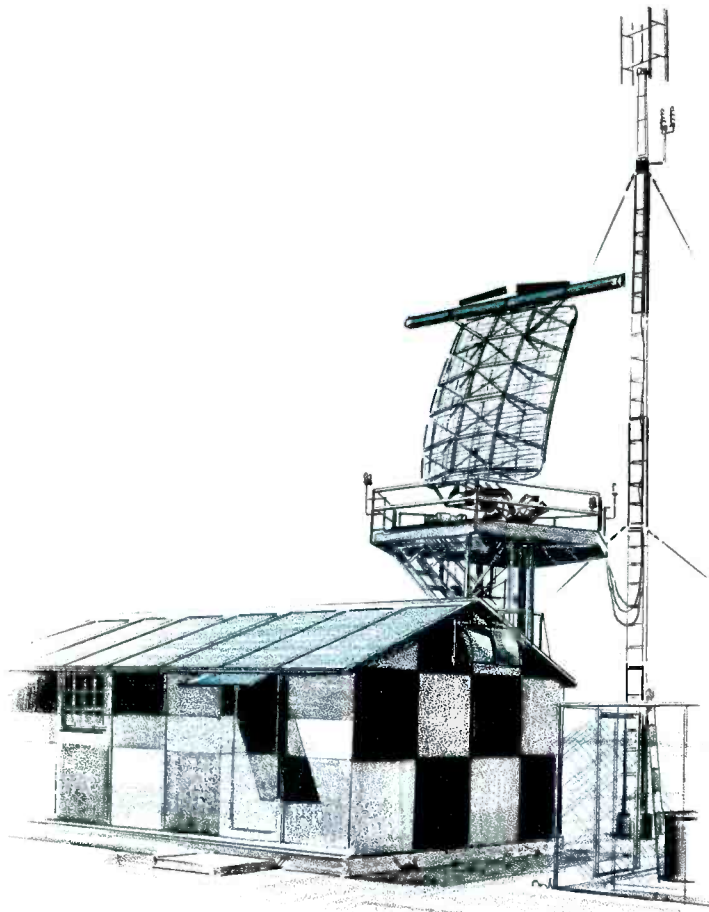
Wilcox Transponders

Introduction

The increase of air traffic, both civil and military, has necessitated the use of a system for positive control of the separation of active aircraft in a safe efficient manner. The system is a secondary surveillance radar more commonly known as the Air Traffic Control Radar Beacon System (ATCRBS).

The ATCRBS in use today was developed in World War II, due to a need for identifying an aircraft as friend or foe. This system used equipment on the ground to transmit an interrogation signal to the aircraft and a receiver-transmitter in the aircraft to transmit a response back to the ground station. The interrogation signal was received by the aircraft receiver and decoded. If the receiver-transmitter in the aircraft were set to respond to the interrogation, the transmitter sent a coded reply signal to the ground station. The signal was received and decoded by the ground equipment and presented on a radar Plan Position Indicator (PPI) indicator. If the response conformed with the established coding, the aircraft was assumed to be friendly. This was known as an IFF (Identification Friend or Foe) System and has been the basis for the development of the ATCRBS.

The function of the radar beacon in today's environment of air traffic control is to provide positive indentification of individual aircraft rather than identification friend or foe. Normally a ground radar PPI display shows only azimuth and distance of aircraft in the area. However, the traffic controller needs a three-dimensional picture to adequately maintain aircraft separation. To achieve this the ground station transmits two modes of interrogation, one mode for range and azimuth, another mode for altitude or height. The altitude information is given to the aircraft beacon by a separate altimeter in the aircraft. The altimeter pulse codes the aircraft beacon and upon a proper mode of interrogation, replies to the ground station with flight altitude information.

Thereby we have an extremely versatile secondary surveillance radar system which for civil usage provides positive three-dimensional control and in a military usage supplies IFF information.

1955: The beginning of the Beacon program

The Wilcox Electric Company designed an Air Traffic Control Radar Beacon in 1955, which was designated the Wilcox 714A. Since that time the company has maintained a successful development program which has resulted in those equipments shown in Figure 1. The 714D, 814B
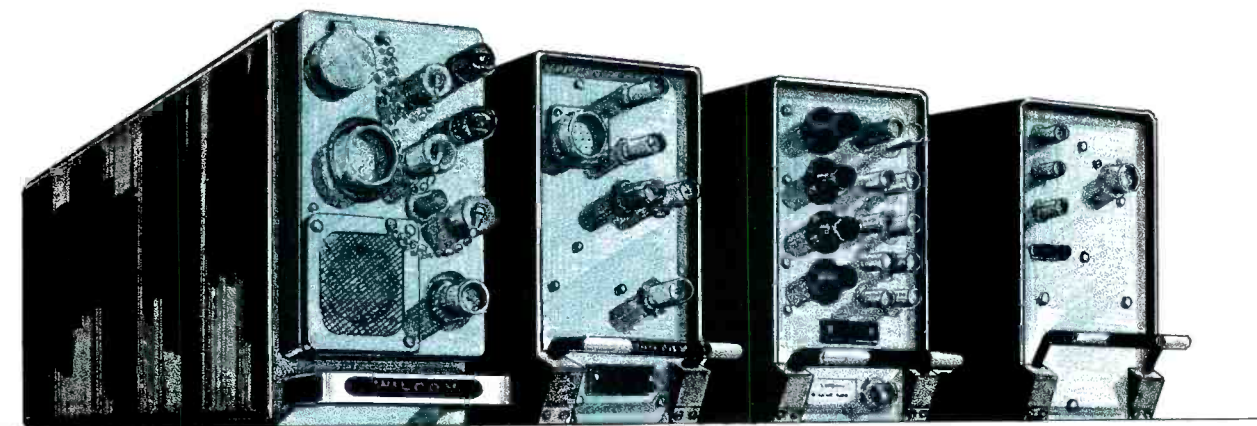
for Air Traffic Control

By RICHARD W. DONOVAN,
Project Group Leader,
Wilcox Electric Co., Inc.

and 914A are for commercial airline or civil use.

The 714D is a hybrid unit in that vacuum tubes and transistors are used extensively. The 814 General Aviation Transponder (GAT) evolved under an FAA development contract for service in the general aviation or executive aircraft industry. Nearly 1000 of the 814 units have been produced. The 914X is a transistorized all mode capability military IFF transponder designed to MIL-E-5400, Class II, and the U.S. National Standard ATCRBS specification. The 914 transponder is presently in production with deliveries starting in May for 250 units.

Figure 2 shows the 914 Transponder with the covers removed. The basic construction is modular, with plug-in assemblies. Figure 3 is a view showing some of the modules removed and illustrating the ease of maintenance and accessibility designed into the 914.

Figure 4 is the 814 Transponder with covers removed. This unit utilizes hinged assemblies which swing out for accessibility and maintenance, rather than plug-in.

The 814 GAT is designed as a low cost, low weight (11 lbs.) transponder meeting the FAA TSO-C74 requirements. It contains both Mode A and Mode C interrogation modes, each having 4096 possible reply codes. The

transmitter output power is a nominal 500 watts peak. The 814 is certified to an environment of $-15°C$ to $+55°C$ and 30,000 feet altitude. On special applications, modification can be made which allows the unit to operate at 50,000 feet altitude.

The 914 is the latest design now in production by Wilcox. Silicon transistors are used exclusively to permit operation under greater temperature extremes. The unit is designed to meet ARINC 532D and FAA TSO-C74, Category A. The unit is packaged in a $\frac{1}{2}$ ATR long form factor weighing 18 pounds. This form factor is very ample allowing a great deal of freedom to provide accessibility in the interest of maintenance. Reliability has been a prime consideration in selecting the components and the final design. Reliability analysis has shown that a guaranteed aircraft removal rate of 2000 hours can be given. What has made this rate possible has been in selection of components which have low failure rates. Tantalum capacitors have been minimized and replaced by mylar foils. Moving parts such as relays and switches have been eliminated or replaced by diode switching and semiconductor devices. All heat generating devices such as the transmitter and voltage regulator are provided special heat sinks and dissipating areas, allow-

ing heat conduction to the external surfaces rather than within. The whole rear panel is a finned casting and is used as a heat sink for the transistorized dc line regulator.

A self test module is included within the equipment. Dynamic transponder operation is checked and monitored while in flight, or if desirable a pre-flight test is made. The testor generates Mode A, 1030 mc rf pulses which interrogate the transponder. If the transponder is operational, then the transmitter will be fired and the tester receives the 1090 mc energy of the transmitted reply pulses and cause a light to indicate proper operation. In this manner receiver frequency, receiver sensitivity, decoder, encoder and transmitter power are tested and monitored to establish limits. Experience has shown that these tests give a very high degree of assurance that the transponder is completely operational.

The receiver front end assembly is fixed tuned, requiring no maintenance adjustment. The receiver IF amplifier incorporates a band pass filter for selectivity with all stages transistorized.

Transmitter Modules

The transmitter modules shown in Figure 5 are for the 914 and 814. The lower one is for the 814 GAT Transponder. The black body transmitter assembly is for the 914 and also contains the power supply for the transponder. Both cavities are die cast and silver plated. The upper cavity is an aluminum casting while the lower is a brass casting. Since both cavities are very similar in internal construction, only the 914 cavity will be discussed. The 914 cavity cross sectional view is shown in Figure 6. The basic difference between the 814 and 914 cavities is that the power supply is part of the assembly in the 914. Construction is such as to dissipate the maximum amount of heat by radiation, as at high altitudes very little air is available to conduct heat. The castings are provided with "O" ring seals

Figure 1 — Air Traffic Control Radar Beacons developed by The Wilcox Electric Company in a program beginning in 1955 with the Model 714A. From the left: Model 714D, 814B and 914A for commercial airline or civil use; Model 914X an all mode unit for military use.
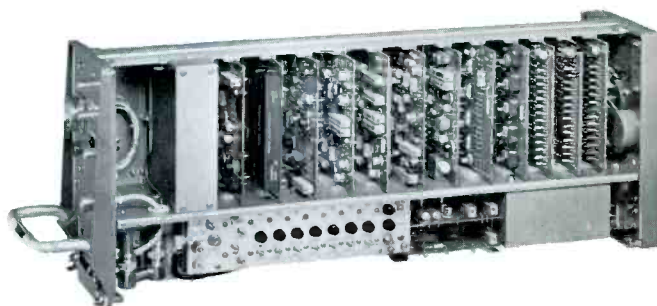

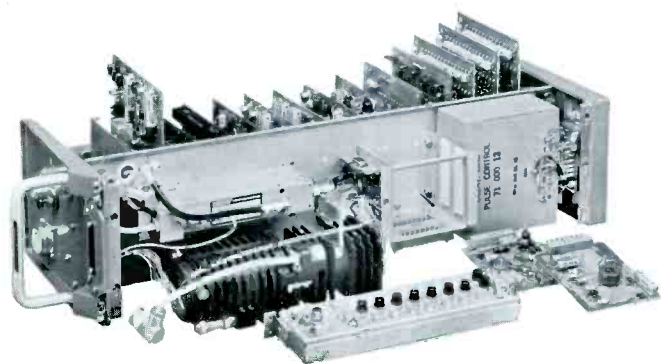Figure 2 — The 914 Transponder with covers removed.

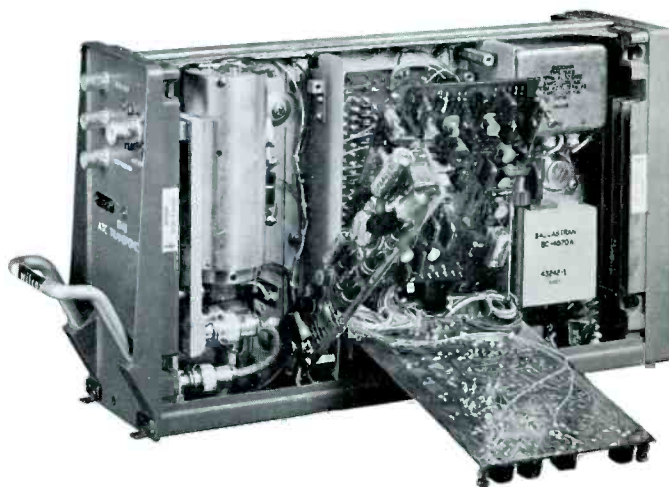Figure 3 — The 914 Transponder with modules removed.

Figure 4 — The 814 GAT Transponder with covers removed. This model utilizes hinged assemblies.

to maintain atmospheric pressure inside the cavity while the external ambient pressure goes up to 80,000 feet. Thus any difficulties from corona or high voltage breakdown are eliminated.

The H.V. power supply section contains a DC to DC converter operating at 10 kilocycles. The converting transformer on the left provides the end seal for this assembly. Transmitter tuning comes out this end also to the front panel for easy accessibility. The high voltage rectifier filter capacitors and bleeder resistors are mounted in a pack shown in Fig. 6 that is keyed and slips into the power supply section casting. The H. V. power supply provides a nominal 2000 volts at 15 ma. and is adjustable in three steps of 1800 volts, 2000 volts and 2200 volts. These adjustable steps allow the transmitter power to be maintained at a nominal 500 watts peak as the tube degrades with life.

Planar Triodes in Beacon

The 914 Transmitter uses a Machlett 7855 while the
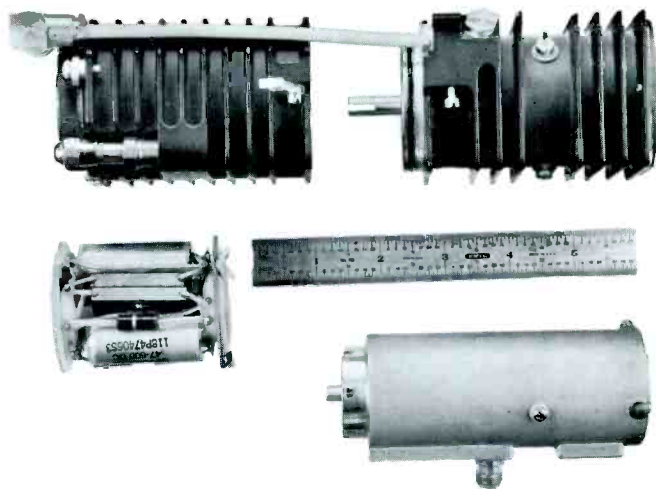
Figure 5 — Transmitter modules for the 914 (upper) and 814 Transponder (lower).

Figure 6 — Cross section view of the 914 cavity.

GRID-CATHODE SECTION

GRID-PLATE SECTION

TRANSFORMER

TRANSMITTER CAVITY

H.V. POWER SUPPLY
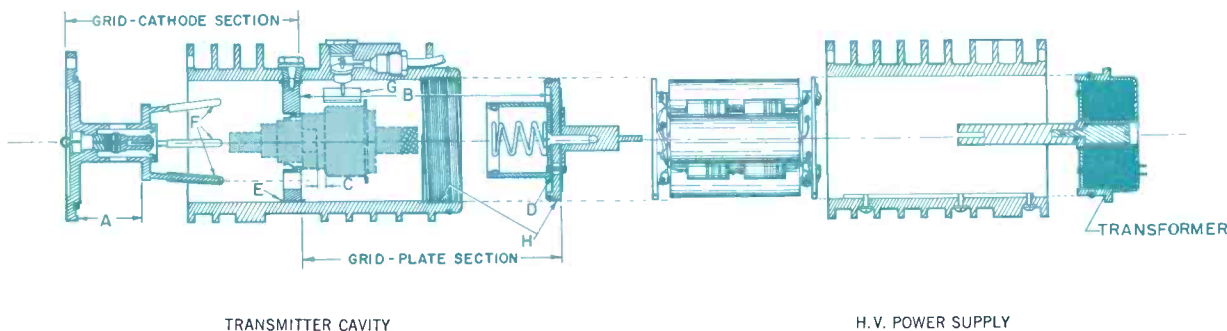
A – cathode cavity inductance
B – plate cavity inductance
C – grid-to-plate interelectrode capacitance
D – plate by plate capacitance
E – grid by-pass capacity
F – feed back capacity
G – output coupling capacity
H – frequency adjust

814 GAT uses the Machlett 7815. The GAT environmental temperature extremes are much less than those of the 914 and thus the anode temperature stabilized tube is not essential. Both cavities are capacitive coupled into diplexers and then coupled to the antenna transmission line. However, the 914 uses a ferrite isolator between the diplexer and transmitter. The isolator isolates the antenna load from the transmitter by 10 db, allowing a transmission line load mismatch of 4:1 without appreciable frequency shift of the transmitter. The measured frequency shift with a 4:1 VSWR is less than 1.5 mc.

The 914 transmitter design is a grid-separation tuned-plate tuned-grid oscillator using grid pulsing. A constant DC voltage is maintained on the plate of the 7855 triode.

The grid is biased beyond cutoff at —100 volts. The modulator pulses the grid 20 volts positive exciting the cavity to its self resonant frequency.

In Figure 6, which shows the transmitter cavity design, cathode assembly A provides the feedback element F, which maintain the proper phase relationship between the grid-cathode section and the grid plate section. Teflon dielectric is slipped over the feedback probes to prevent voltage breakdown. The grid is —100 volts above DC ground, AC ground is provided by the grid by-pass capacity E, which is a teflon tape assembled to the grid and into the casting through a shrink fitting process. In this way constant by-pass capacity, regardless of the mechanical tolerances and temperature differentials, is maintained.

The grid-plate section is tuned by the frequency adjust H and tunes the plate cavity inductance B. The inductance is such as to form parallel resonance with the grid to plate interelectrode capacitance C. The plate is by-passed by 3 mil mica discs, D.

The rf is coupled from the cavity by the capacitive probe G. Since the plate voltage is adjusted in steps to increase power due to the tube degradation, the coupling is fixed and requires no adjustment. The cavity is coupled for a nominal 500 watts which is required for certification, however, during the development it was demonstrated that 1000 watts can be coupled with minor adjustments to the feedback and coupling probes.

Use of Frequency Stable Triodes

Frequency stability of the final cavity designs is shown in Figure 7. Stability has been achieved without the use of special materials such as invar and kovar. The cavities are stress relieved to the full anealed condition of the material prior to final machining. The grid by-pass capacitor is shrink fitted to insure a constant capacity due to any mechanical dimensional changes that may occur throughout the temperature range. The plate by-pass is mica which has excellent mechanical stability through the temperature extremes. The curves are quite significant and illustrate the ability of the 7855 to temperature compensate the Wilcox cavity design. It should be noted that slight modifi-

Figure 7 — Frequency stability of final cavity design. The ML-7855 frequency stable tube is employed to provide this stable characteristic.

ML 7855			ML 7815	
°C	FREQUENCY		°C	FREQUENCY
+100	1090.9		+100	1087.3
+75	1090.7		+75	1087.5
+50	1090.5		+50	1088.5
+27	1090.0		+25	1089.6
0	1089.5		0	1091.5
−25	1089.6		−25	1092.1
−50	1089.0		−50	1092.3
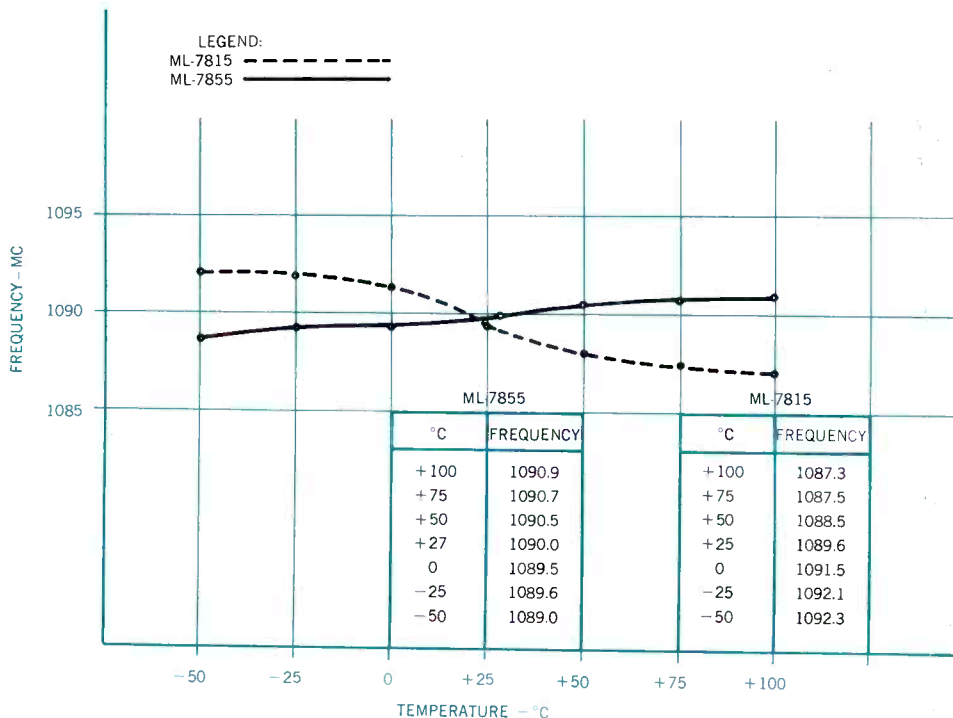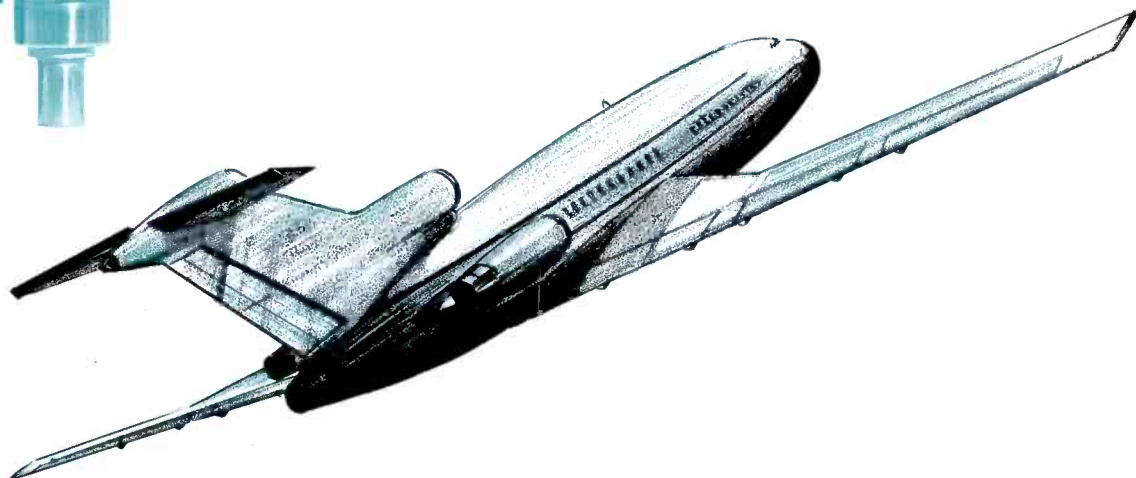
cations to the cathode section was necessary when interchanging the tubes, as they are not dimensionally interchangeable. Electrical performance was essentially the same for both tubes, however, the tuning was adjusted to a shorter length for the 7855.

The 7815 could have been used for the commercial 914 transponder but it was felt a greater margin of stability was desirable as VSWR shift would only add to the total frequency deviation. By using the 7855 tube and combining the frequency shift due to temperature, 4:1 VSWR shift and up to 1% duty cycle shift, the frequency was found to have a maximum excursion around 1090 megacycles of $+2.4$ mc and -2.5 mc. These measurements are well within the specification and are considered very good under present design standards.

Life tests are in process on 7855's in the cavities at this writing. Present data shows that after 600 hours no degradation is being observed. Life tests on the 7815 in the cavities show life in excess of 1200 hours before degradation takes place. Both of the tubes are being grid pulsed in the same circuit at a 1% duty with a nominal 500 watts coupled out. The filament voltage is operated at 5.8 volts rms.

Conclusion

The controlling of air traffic has been made safer and positive with the use of the Air Traffic Control Transponder. The Wilcox Electric Company has been a leader in developing the ATC Transponder system and in continued development of solid state transponders, both for commercial use and military use. The Wilcox 914 and 814 commercial transponders were discussed. Comparison of the ML-7815 and ML-7855 tubes in a Wilcox designed cavity were described showing the basis for their selection in the 814 GAT and 914 airline transponder. The data and design work for this article was performed within the engineering department at the Wilcox Electric Company, 1400 Chestnut Street, Kansas City, Missouri. Acknowledgement is made to Mr. Forest Nichols, Design Engineer, and Mr. John Campbell, Design Technician, for their able assistance in the design and for taking the data as a part of this article.
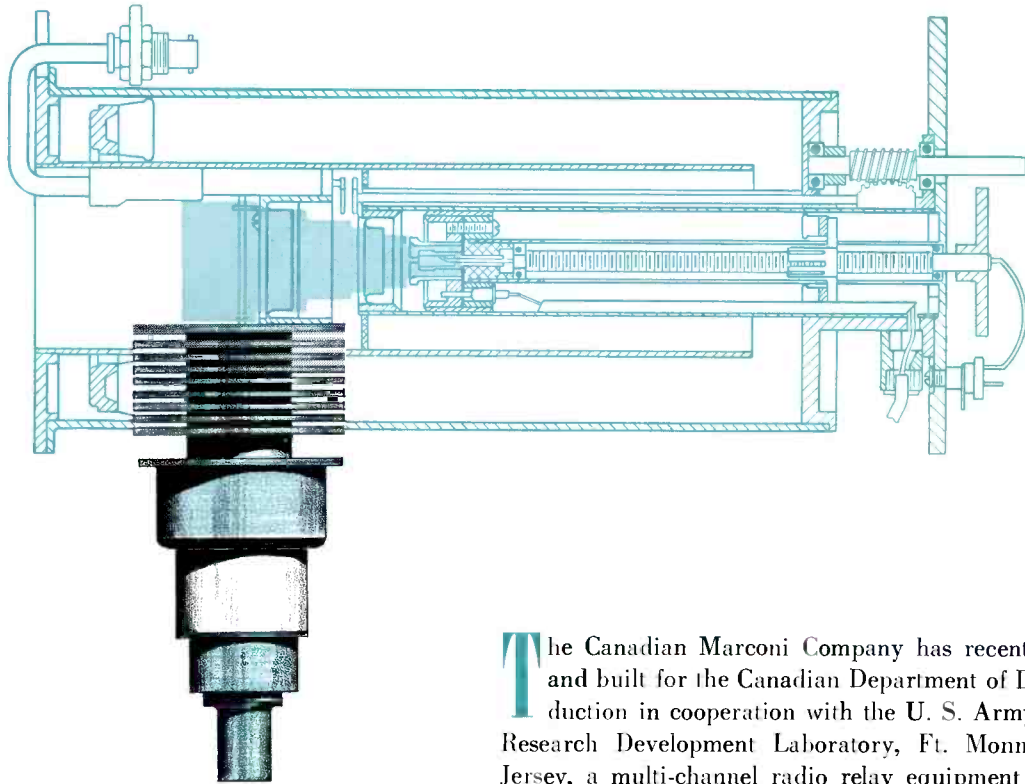
The Canadian Marconi Company has recently designed and built for the Canadian Department of Defense Production in cooperation with the U. S. Army Electronic Research Development Laboratory, Ft. Monmouth, New Jersey, a multi-channel radio relay equipment for tactical use. To obtain the desired reliability the equipment utilizes standard components derated as required. Whereas this method provides assurance for continued operation under the stress of field conditions it also provides the possibility of higher powered performance under stable or "on-site" conditions. Stringent size requirements were dictated by limited availability of vehicular space; specifications called also for rapid tuning across the band to be covered. These varying needs have been satisfactorily met in the design of this equipment.

Three transmitter power amplifier heads are used in the equipment to cover a broad frequency range, each rf head covering a range of approximately one octave in the UHF frequency range. Each power amplifier employs two ML-7211 tubes in the two stages of amplification; power output is 30 to 40 watts. To facilitate ease of maintenance all units are "slide-in/plug-in" to thereby eliminate cabling as well as providing quick field service.

Design Development

Prior to the establishment of the final transmitter design (quarter-wave cavity amplifier using planar triodes), several other methods were considered. Among these was a strip line cavity using a miniature tetrode. Mechanical complexities, problems associated with adequate bandwidth (as related to high capacitance in the tube) and screen bypassing prompted consideration of the planar triode-coaxial cavity combination. The triodes proved easier to tune, required simpler contact assemblies and had gain and efficiency equal

A Multi-Channel Radio Relay for Tactical Use

As told to Cathode Press by N. F. HAMILTON-PIERCY, Development Engineer
Telecommunications Department, Commercial Products Division
Canadian Marconi Company

to or better than that of the tetrodes. It was at this point that the planar triode, ML-7211, was chosen over the ML-7289 triode, the former tube offering considerably higher power under either full or derated power operation.

Use of coaxial quater-wave resonators or cavities was established after experimental results had shown that other devices, notably the variable inductance tuner, did not offer the long term reliability required. Three resonators were designed, one for each rf band to be covered. Of unusual interest is the folded quarter-wave cavity used with the lowest frequency band, Band I. See Figure 1.

Amplifier Design — Band I

The size limitations imposed on the Band I amplifier section of the radio relay provided a most interesting design challenge. Using the planar triode ML-7211 with a plate capacitance of 2.3 pf and with no further capacitance loading, it was apparent that the resonator would have been too long to be accommodated within the required 10 inches of length. By increasing the characteristic impedance to a very high value or by further capacity loading, the required short length could be achieved, but both bandwidth and efficiency would have suffered; also the cross sectional dimensions would have been excessive. The method adopted was to use a folded or re-entrant resonator in the plate circuit. The physical design was established such that the mean cavity length very closely approximates the electrical length. In Figure 2, the re-entrant configuration is compared to the standard configuration. It will be noted that the capacity probe used for the output coupling is normally found in the plate line. Here, however, it was necessary to incorporate the movable probe in the grid line. This presents no problem since the tube operates in a grounded-grid circuit.

The plate resonator was constructed with a characteristic

impedance of about 38 ohms and the cathode resonator with an impedance of about 53 ohms. These impedances were determined after considering mechanical size and the provision of a large ratio of C_aZ_{oa} to C_kZ_{ok} for stability. The capacitive losses were kept to a minimum by designing around this order of impedance.

Using conventional triode amplifier theory it can be seen that a load between 1000 and 2000 ohms satisfies the requirement for a power output in excess of 30 watts from a 600 volt supply, with the tube operating at approximately 50% efficiency. Using the highest load value:

$$Q_L = \frac{R_L (\Theta + \sin\Theta \cos\Theta)}{2 Z_o \sin^2\Theta}$$

where $R_L = 2K$ ohms

$$\tan\Theta = \frac{1}{\omega C Z_o} \text{ where } C = 2.3 \text{ pf for the ML-7211}$$

$$Z_o = 38 \text{ ohms}$$

A 3 db bandwidth is obtained with a Q_L of 42 to 43. By increasing coupling at the lower frequency portion of the rf band the bandwidth may be kept relatively constant over the entire band.

Re-entrant plate cavity dimensions were determined by first equating the total length of the cavity for a 2.3 pf loading capacitor and a 38 ohms impedance, then determining the portion needed to tune over the required band. The remainder of the cavity is then folded back such that its mean geometric length is equal to that portion of the basic cavity from the upper band tuning point to the tube grid-plate space. Care has been taken to insure that the 38 ohms impedance is maintained as far as possible. Plate dc isolation and rf bypass is maintained by a thin mica spacer. Figure 3 illustrates the power amplifier schematic diagram for Band I.

The driver amplifier and output amplifier can be made mechanically identical, the only difference being the choice

of the dc operating point. This gives a convenient arrangement for gang tuning and the plate resonators can share a common drive screw. However, the output matching conditions are different and individual drives are required for the output probes.

Cathode Circuit

The cathode line of the cavity is conventional, heavily loaded with capacitance and consists of a brass cylinder within a teflon cylinder. By this means the insulation, dielectric, and support for the de-coupling capacitors are built into the cathode assembly, itself consisting of three ceramic feed-throughs. Ac input to the cathode, dc cathode bias and one side of the heater supply are taken by a coaxial lead soldered to the face of the grid cavity and, by direct connection, terminated by the cathode. A low pass filter isolates the input signal from cathode dc and ac voltages. Heater voltage to the cathode is obtained from a well stabilized 5.5 volt source. (The 5.5 volt figure was established after extensive experience with operation of the 3CX100A5 tube and is chosen for maximum life in operation; all other tube operating voltages are obtained from this same source.)

The cathode supply circuit is driven by a dc amplifier

Figure 1 — Quarter-wave re-entrant cavity for Band I transmitter.
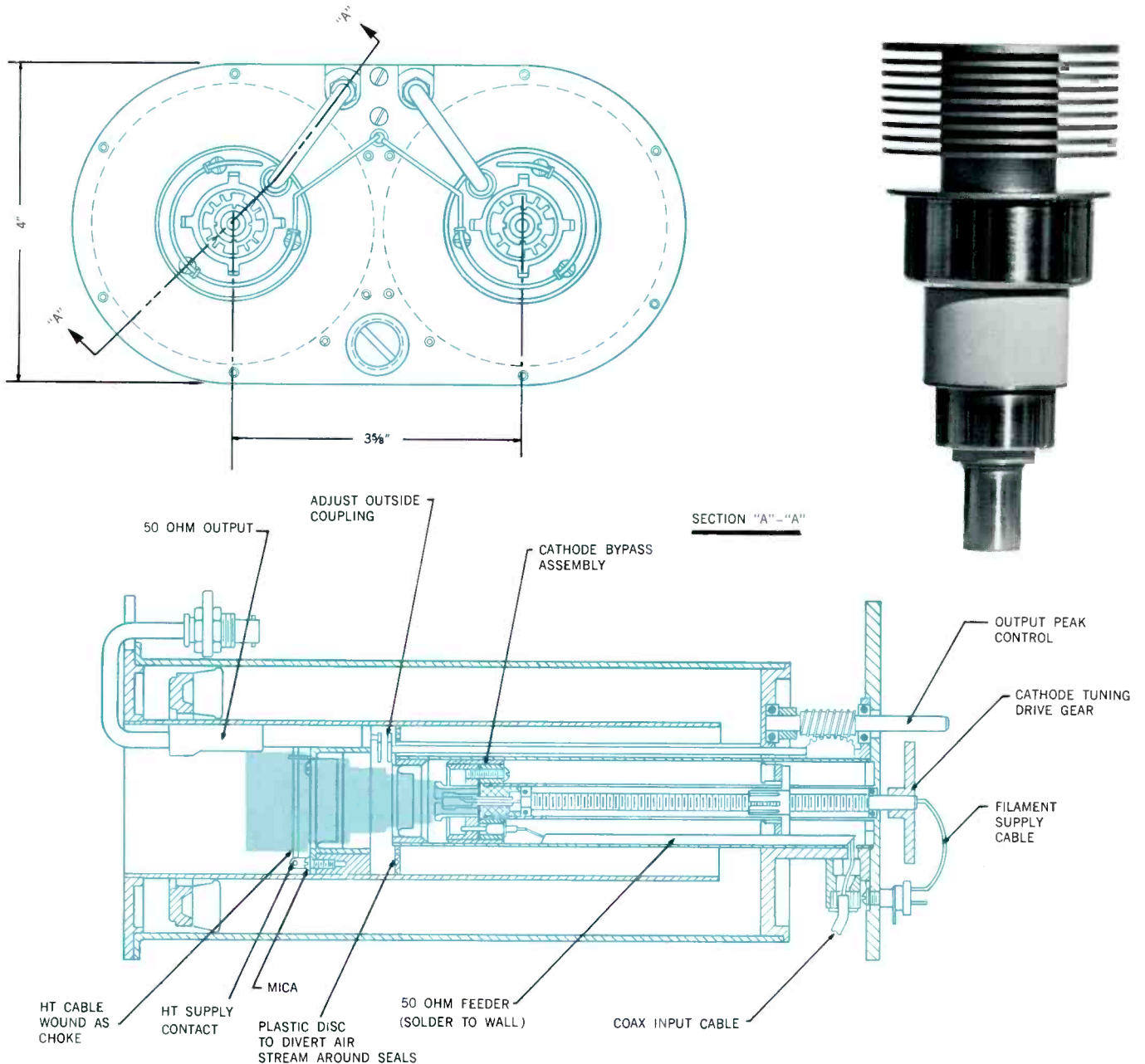
which is, in effect, a constant current series source. This provision is made to limit the driver amplifier output to prevent overdriving of the output stage and to protect the amplifier tube grids. In addition, the constant cathode current maintains a constant G_m and good match. Figure 4 shows a schematic view of the constant current regulator.

Cathode self bias is used and the dc is supplied via the signal input lead. As mentioned previously, a large amount of capacity loading is used such that the resonator length remains short and a large $C_k Z_{ok}$ value is maintained.

Amplifier Performance

Measurements of the Band I amplifier show that gains up to 11.3 db can be achieved across the band with power output in excess of 30 watts. Indeed, power as high as 50 watts could be reached with 9.6 db gain when all circuits were aligned, the efficiency being greater than 50% under these conditions. Bandwidths in general were between the two theoretical values although a slight loss of gain was noticed when the probes were set for bandwidth considerations rather than for maximum power output.

The amplifier run as a driver gave gains in the order of 17 db with an efficiency around 33% and an output of 9 watts. The driver input match was very dependent on plate current, and for a good match the minimum current was in the order of 50 mA, the match being between 1.8 and 1.2 VSWR across the band. Stability of match was enhanced by use of the constant current dc cathode feed previously described. Transmitter performance characteristics are summarized in Figures 5a, 5b, 5c, 5d and 5e.

Mechanical Considerations

Cooling: Because of the construction of the re-entrant portion of the cavity, the tube plate radiator is obscured. Since space between the end of the amplifier and the back face of the transmitter box is not large, a special ducting was devised. With an air flow of about 15 cubic feet per minute (well in excess of that normally required to dissipate the anode heat) the hottest point around the anode does not exceed 180°C under any operating condition. A small portion of the air is taken through spaced voids in the spring fingers and passes over the grid and cathode seals.

Ambient air temperature conditions over which the proper cavity/tube temperatures should be maintained range from plus 75°C to minus 45°C. Maximum altitude for operation is 10,000 feet.

General: The cavity is made from aluminum. It is finished with a copper flash over a zinc base, the copper being heavily plated with gold. The gold is very durable, resists corrosion and provides a good contact surface for the spring fingers.

The spring finger sockets employ chamfered cathode contact entry points and provide good centering for the tube and are of very durable construction. The overall shape of the contact fingers is conical.

CONVENTIONAL COAXIAL AMPLIFIER CONFIGURATION

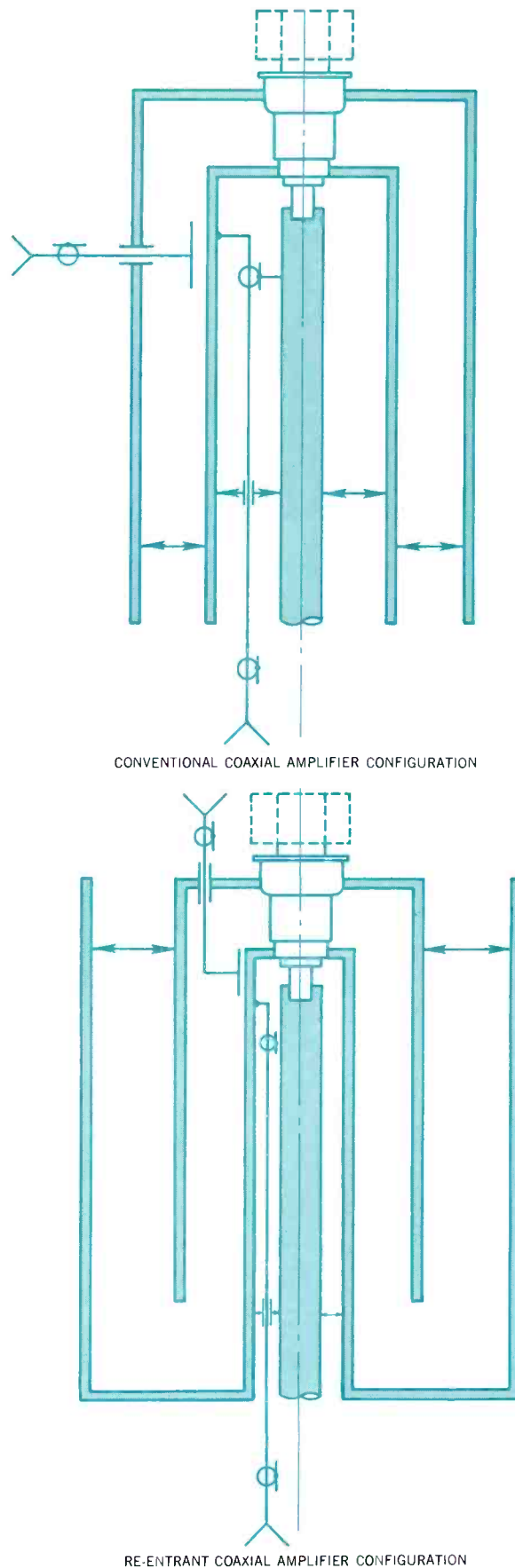RE-ENTRANT COAXIAL AMPLIFIER CONFIGURATION

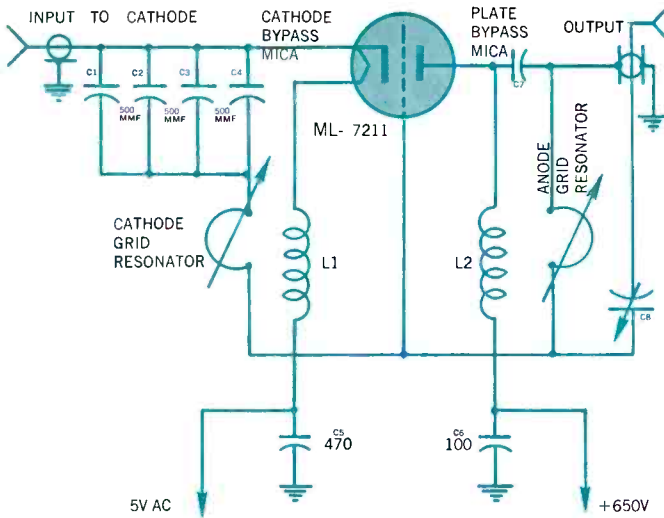Figure 2 — Comparison of normal and re-entrant amplifier designs.

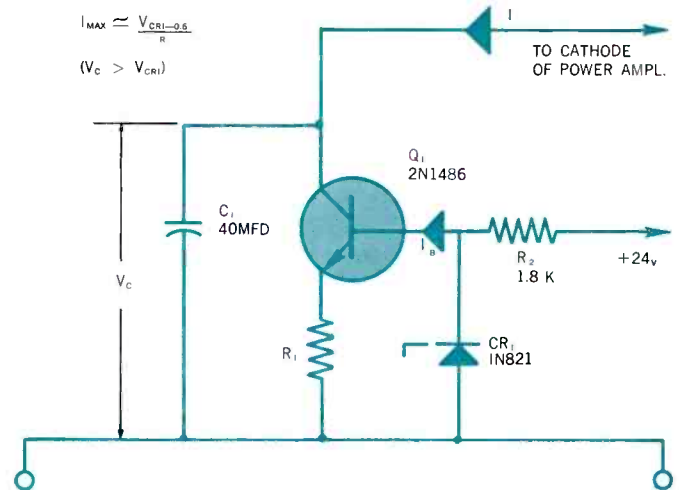Figure 3 — Band I power amplifier schematic design.
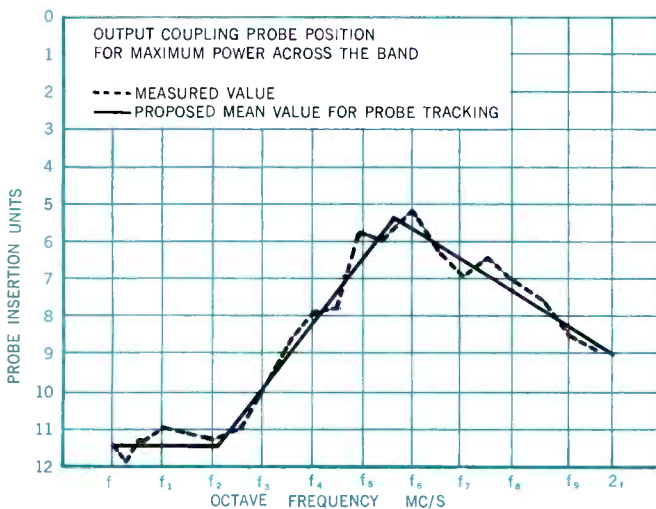

Figure 4 — Constant current regulator.

Figure 5a — Band I amplifier probe tracking the maximum excursion of the probe represents a movement of 1/32" using a profiled cam.
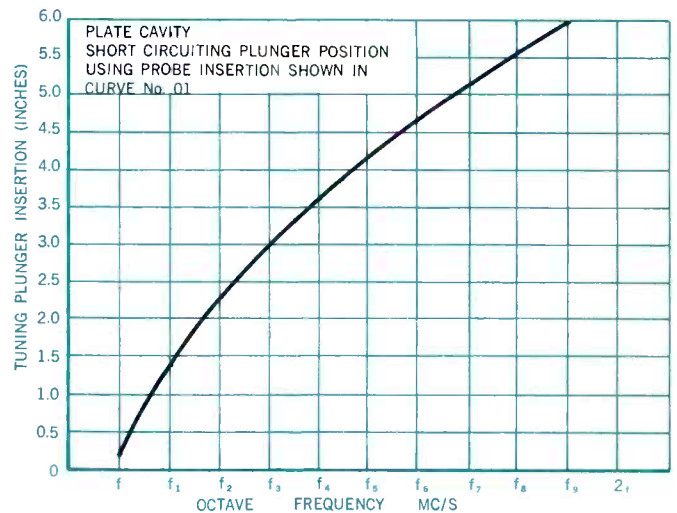
Figure 5b — Band I amplifier tuning plot follows a nearly linear curve.

Amplifier Design

High Frequency Bands: Amplifiers for Bands II and III use a conventional/nonre-entrant cavity design employing a grounded-grid configuration, direct coupled input to the cathode and capacity probe output. The ML-7211 planar triode is employed in both amplifiers. The performance of both amplifiers is similar to that obtained for the Band I unit, except that the gain is slightly reduced at the high end of Band III and that the input match of the Band III amplifier requires a $\frac{1}{4}$ wave resonator tapped to act as a transformer.

The usual practices of a large ratio of C_aZ_{oa} to C_kZ_{ok} for stability in the two tank circuits are followed. The plate circuit is designed for a high unloaded "Q" for maximum rf efficiency. The impedance of the circuit is 55 ohms with the outside tube diameter a maximum for the available space.

The cathode circuit and dc operating points for driver and output stages are essentially the same as for the Band I unit. Cooling of the tubes is simplified by the cavity construction.

Conclusion: The three amplifiers meet all requirements of power, bandwidth and size. Their efficiency is reasonably high for a triode amplifier at these frequencies. Life and general reliability should be good as care has been taken to operate the planar triodes conservatively and overall construction is rugged.

Considerations in the Choice of the ML-7211

In the design of these amplifiers, an evaluation program including both study and experimental test was undertaken

Figure 5c — Power output across the band and Band I amplifier.

Figure 5d — Drive vs. output at lower end of Band I.
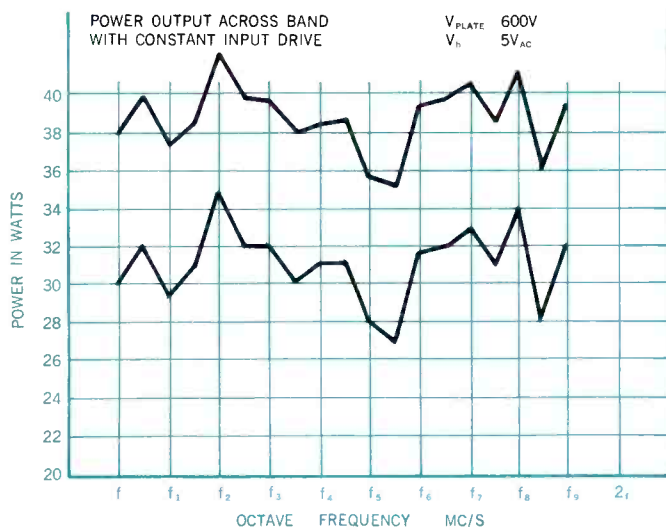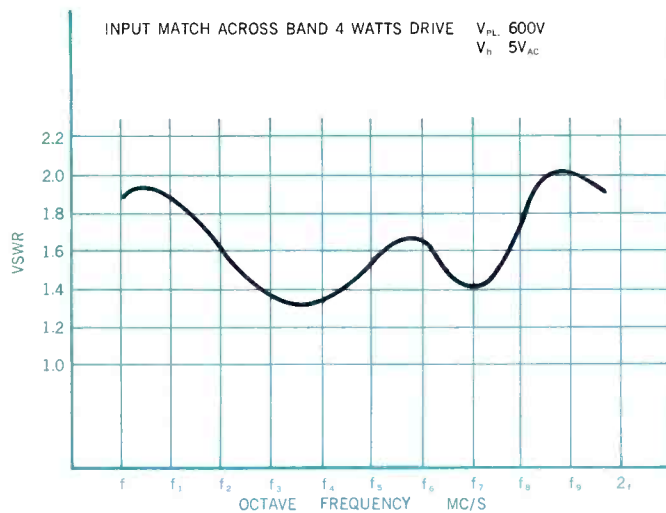

Figure 5e — Input match across Band I.

to determine the type of tube to be employed. This program indicated the use of the ML-7211 tube, for the following reasons —

1. With the 7211 tube, power output meeting equipment requirements with adequate margin can be achieved under conservative operating conditions.

2. The 7211 tube offers good power output in relation to the volume of the tube, permitting relatively compact assemblies.

3. Experience with this and previous tubes of the same family shows that reliable long life performance can be achieved.

4. In the UHF frequency range, the 7211 offers gain and efficiency comparable with the best offered by any other tubes commercially available at this time.

5. The construction of the 7211 meets the requirements for ruggedness imposed by the application of the equipment to mobile tactical use.

6. The 7211 exhibits good uniformity from tube to tube, providing ease of replacement in the field.

7. The input impedance of the cathode is suitable for simple direct coupling.

8. In the event of field emergency, a 7211 tube may be replaced directly by other tubes of the same family such as the 3CX100A5 or 2C39. In this case, some loss of gain and reduction of output must be expected, but the equipment can be kept in operation.

Summary

A description has been given of the design of power amplifiers for use in a UHF radio relay equipment designed for mobile tactical applications. Considerations of high reliability, reduction in space occupied, and exceptionally wide tuning range, have greatly influenced the design. In particular, a re-entrant cavity design is described which was designed to meet requirements of limited cavity length in the lower frequency ranges of the equipment. Careful consideration of a variety of tube types led to the selection of the 7211 triode used in a grounded grid configuration for this service.
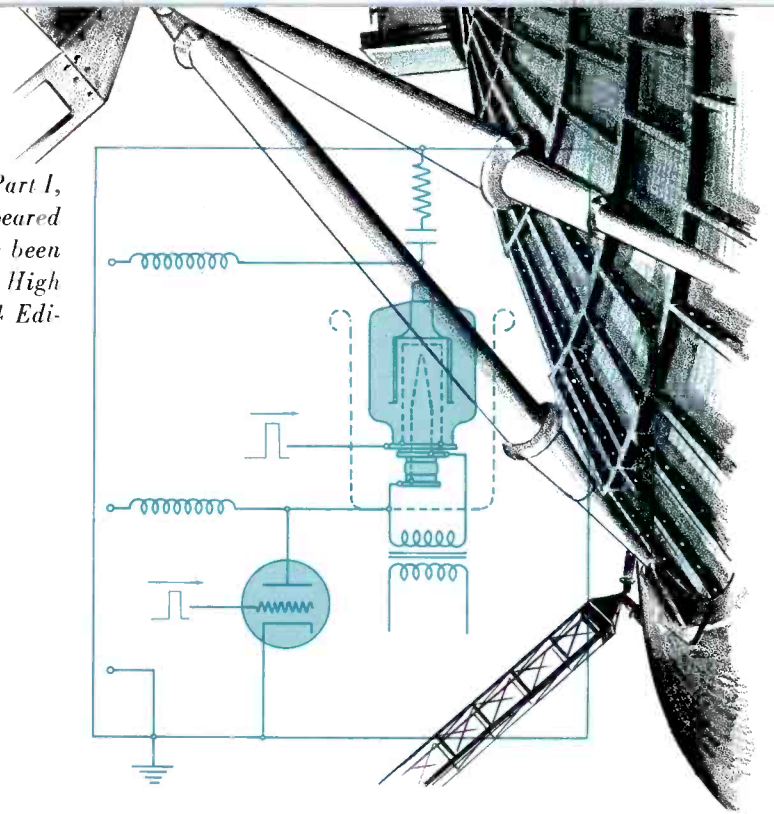
Interactions Between Pulse Modulator Tubes

In the previous sections the discussion has centered on tube design parameters and the variations in characteristics by tube type. In the present section the phenomena of tube behavior in various circuit situations will be discussed.

1. Pulse Width, Pulse Repetition Rate and Pulse Rise Time.

In tubes with thoriated-tungsten cathodes the maximum pulse width is not limited by the emitter itself. Usually the control grid temperature is the limiting factor. In the case of tetrodes the screen-grid temperature is usually the limiting factor. The tube data sheet gives both a maximum pulse width and a maximum average grid dissipation. It is reasonable to assume that wider pulses could be used if the peak power were reduced accordingly. Peak grid dissipation is the product of the peak positive grid voltages with respect to the cathode multiplied by the peak grid conduction current. Equation (7) shows that the product of the pulse width by the peak power is a constant for a fixed grid temperature rise. If the rate of diffusion of heat from the wire surface into the volume of the wire is taken into account, $p_g \propto \tau^{1/2}$ is a constant limited by maximum permissible surface grid temperature. This relation permits an approximate extrapolation between peak power in the grid and pulse length, i.e., if a tube has a typical rating giving e_g, i_g, and τ max, the peak grid dissipation can be increased for shorter pulse widths according to the above relation. Of course the average grid dissipation cannot be exceeded.

Only electron conduction currents to the various tube electrodes can give rise to electrode dissipation. Capacitance charging currents in the effective tube input capacitance do not result in any control grid dissipation. For this reason grid dissipation is not affected by wide variations in the pulse recurrence frequency at constant duty. If the screen grid voltage is kept constant, the dissipation in this grid is independent of pulse width and repetition rate and is simply E_{sg} x I_{sg}, where I_{sg} is the average screen-grid current. If a tetrode is operated close to or below the knee of the plate current curves on the constant grid drive characteristic curves, the screen-grid current may increase substantially and E_{sg} may not be constant during a pulse. A graphical integration of e_{sg} x i_{sg} for a single pulse may be used to determine the screen dissipation.

When short pulses are used, the repetition rates may be high. Although high repetition rates do not affect the manner of calculating grid dissipations, they do make a great difference as regards anode dissipation. In this case it is possible to do a graphical integration of i_p x e_p as for screen grid case above. To do so would require a detailed calculation from the load line on the characteristic curves. Fortunately there is a much simpler method which may be used. The output capacitance of the tube together with any circuit capacitance between plate and cathode must be charged or discharged by the amplitude of the output voltage pulse. Since these capacitance currents must be furnished by conduction current through the tube, and since the tube resistance is large compared with other resistance in the charging circuit, nearly all these charging or discharging losses will show up as anode dissipation. Since this energy is put into

Vacuum Power Tubes For Pulse Modulation

by Dr. H. D. DOOLITTLE
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Part 2

and Circuits

the anode on every pulse, the plate dissipation P_d now becomes,

$$P_d = e_p \times i_p + \frac{1}{2} C_{out} (E_{bb}^2 - e_p^2) \times p_{rr} \qquad (15)$$

Here e_p and i_p refer to the instantaneous tube drop and plate current during the flat top of the pulse, C_{out} is the total stray capacitance which is discharged (or charged), and p_{rr} is the pulse repetition rate. For very high pulse repetition rates, the term $e_p \times i_p$ may become negligible. When that happens the efficiency of the switching operation is low. Dolan[15] has discussed this subject in more detail.

In floating deck type modulators used to switch modulating anodes of klystrons, the capacitance charging current usually exceeds the resistive component of the load current. Swanson[16] has discussed tube ratings for such cases. It should be noted that the average plate dissipation depends only on $1/2 \, C \, V^2 \times p_{rr}$ and is not affected by the rise time of the pulse. Of course the peak anode dissipation is dependent on the rise time.

The added losses due to charging or discharging stray capacitance is not peculiar to vacuum tube modulators. Any time a capacitance is charged (except for inductance charging) the efficiency is fifty per cent. Any time a capacitor is discharged into a non-useful load, the energy is thrown away. Line type modulators cannot be matched into a capacitative load and tube plus stray circuit capacitance is discharged into a non-useful load. The P_b factor in hydrogen thyratrons is based on this reasoning. With a gas tube this energy may be partially dissipated in circuit resistance rather than in the tube itself. Unless it is accounted for, some components may be overheated.

For vacuum tubes with oxide cathodes, limits on pulse width and pulse repetition rates as determined by electrode dissipations are the same as for thoriated-tungsten tubes. However, the oxide cathode itself may put additional restrictions on the pulse length. It is well known that currents of 20 to 100 amperes per square centimeter are obtainable for microsecond pulses from oxide cathodes in magnetrons and that such high current densities cannot be maintained for pulses greater than a few microseconds. The situation in oxide cathode pulse tubes is quite different. It has been shown in equation (5) that space charge in the outer grid to anode spacing limits cathode emission in practical tubes to a few amperes per square centimeter. Pulses of millisecond duration are satisfactory at such low peak current densities. However, as noted in the section on oxide cathodes, it is essential that the tube be monitored in production at the maximum pulse width for which it is rated and used.

Excessive average electrode dissipation or high envelope temperature may lead to an increase in the gas level of a tube which in turn may cause cathode deterioration. If the gas reacts chemically with the cathode, the pulse current will decrease during the pulse. If the released gas is hydrogen, and the pressure is high enough, it will ionize and reduce the space charge either at the cathode or between screen grid and anode. The net result may be an increase in pulse current during the pulse. Since positive ions move much slower than electrons, it may take a time of the order of microseconds before the effect becomes apparent.

If short pulse rise time is required, the cathode must be capable of providing the necessary peak current to charge the stray capacitance. This current may be considerably greater than the load current. For this application, the oxide cathode has an advantage over thoriated tungsten, since by applying additional drive it is feasible to obtain high currents for fractional microsecond pulses during the time when e_b is high.

2. Grid Drive Requirements and Gain.

An analysis of grid drive requirements for receiving tube pulsed applications has been given by Neeteson[17]. The same general approach may be used with modifications for power switches. It is not the intention here to write an equation for the input pulse in terms of various circuit constants of the input and output circuits, but merely to point out the salient features. If the capacitative currents in both the input and output circuits are small compared with the pure resistance currents, then the output load line of Appendix III will be a straight line. The grid current will increase as the plate voltage falls. Figure 15 shows the instantaneous grid current, i_g, as a function of the instantaneous grid voltage, e_g, for various fixed plate voltages for the 7560 tube. A load line for the input circuit is shown assuming that the open circuit grid drive voltage is e_{g1}. The slope of this line is determined by R_d, the internal resistance of the driver. The

effective total drive is $e_{g1} - i_{go} \times R_d$, where i_{go} is the grid current at the operating point. If the output load has a parallel capacitor such that the capacitative charging current is larger than the pure resistive load current, then the load line of Appendix III will change to that shown in Figure 16, $E_{bb} - Op$. The exact form of this curve will depend on the circuit parameters and the available emission from the tube. Similarly, the fall of the pulse will be determined by the value of an effective RC time constant. Since on the pulse rise the grid of the modulator tube is positive and the tube plate resistance is low, the time constant is considerably smaller than on the pulse fall. In the latter case the modulator tube is open circuited. The capacitance of the tube input circuit has a similar effect on the rate of rise and fall of the driving pulse. If the time constant of the output circuit is greater than that of the input circuit, the drive pulse will have a faster rise time, since the grid conduction current is lower at the higher plate voltages. If the fall time of the grid pulse is slow, it will cause an increase in the fall time of the plate pulse. This is so because the tube will not be cut off due to the slow fall of e_g. Furthermore, whatever plate current flows during this time will cause increased plate dissipation. This type of operation can be used advan-
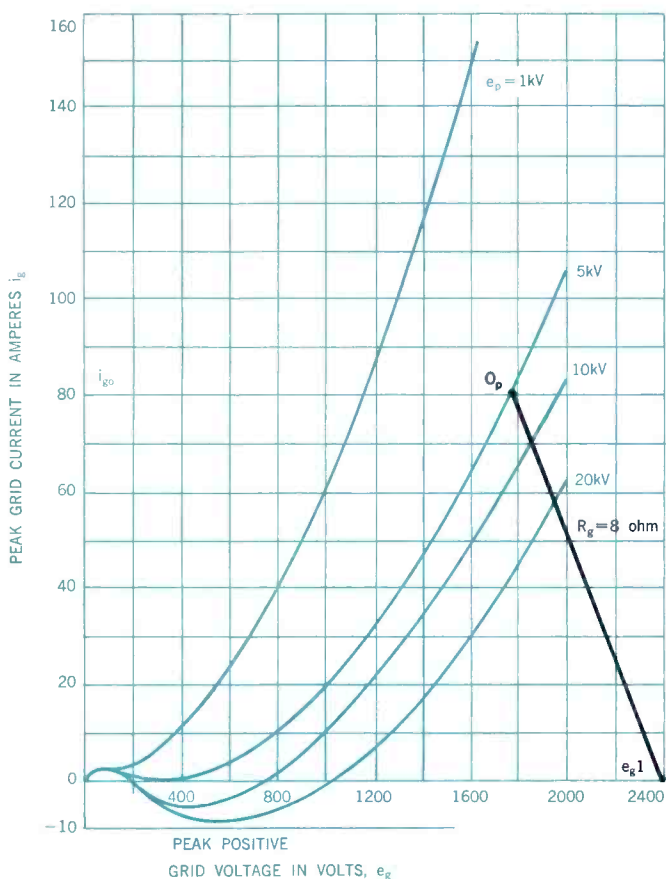
tageously to avoid a fast interruption of plate current, particularly during a fault condition.

It is generally assumed that the higher amplification factor of the tube the greater will be the voltage gain. To obtain a figure for voltage gain it is only necessary to determine the operating point on the characteristic curves and to determine the proper cutoff bias, Ec_c. The voltage gain, A, will be given by

$$A = \frac{E_{bb} - e_p}{e_g + Ec_c} \qquad (17)$$

We can obtain an approximate formula for voltage gain in terms of the amplification factor by using equation 10b and taking the output voltage, E_o as $i_p \times Rl$. The total drive voltage will be $e_g + \dfrac{E_{sg}}{\mu_{sg}} + \dfrac{e_p}{\mu_p}$, and $\dfrac{E_{bb}}{\mu} = - Ec_c$.

Rearranging the above results, the following equation for the voltage gain is obtained,

$$A = \frac{E_o}{E_i} \approx \frac{1}{\dfrac{1}{c\,Rl} + \dfrac{1}{\mu}}$$

If μ is much larger than $c\,Rl$, the formula simplifies to
$$A \approx c\,Rl$$

For example, the μ of a gun type modulator may be practically infinite and only a small cutoff bias is required. If the gun type tube has a relatively low perveance, the voltage gain is usually about the same as for conventional triodes. This figure for voltage gain is the same as that to be used in calculating the effective input capacitance in equation (8). It is apparent that the actual voltage gain has nothing whatever to do with μ unless μ is low enough to require a bias voltage to be used, and then it gives the contribution to total drive by telling how much of the drive is required to overcome the negative grid bias. The voltage gain for triodes is of the order of 10-20, and for tetrodes from 20 to 40. In order to determine the power gain it is necessary to multiply the voltage gain by the current gain. The current gain is obtained by the ratio of i_p/i_g at the chosen operating point. For very low μ triodes, shielded-grid triodes, beamed triode guns and tetrodes, the current gain may be from 10 to 50. For conventional triodes, the current gain will be 3 or 5. The produce of these numbers give power gains of 30 to 100 for triodes and 200 to 2000 for tetrodes or beamed structures. Practical power gains are less than these factors, particularly for the higher gain tubes. It is essential to use a resistor in parallel with the tube input in order to improve stability and reliability. If the control grid current is nearly zero, as in the case of high gain tubes, any parallel input resistor at all substantially reduces gain. Of course, the higher the stage gain, the stiffer are the requirements on driver pulse shape, amplitude control and stray pick-up. It is difficult to set up high power stages with fixed circuitry. Adjustments must be made to accommodate tube variations. This problem is par-

Figure 15 — Input characteristic of ML-7560. Instantaneous Grid Current versus Grid Voltage with Plate Voltage e_p as a parameter.

ticularly important for tubes with oxide cathodes. The life performance of an oxide cathode tube is simply a matter of how much cathode deterioration one can live with. As the cathode bulk resistance slowly increases, the time arrives when one has to replace the tube, raise the drive power or be satisfied with reduced output. The emission holds up in thoriated-tungsten tubes until decarburization of the cathode wire is complete, then emission drops sharply.

3. Some Causes of Circuit Instabilities.

Secondary electron emission from grids or anodes can lead to pulse instabilities. The most common problem in triodes is where secondary grid emission causes a negative grid current area on the characteristic curves. Appendix III shows the region as it appears on the constant plate and grid current characteristic curves for the 6696 tube. Since high power communications transmitters use tuned circuits and follow an essentially resistive load line, the secondary emission area is not too troublesome. Some tube data sheets do not bother to show it. If one uses a load line such as is shown in Appendix III, it could give trouble either in pulsers or radio frequency amplifiers working with a reactive load. The easiest way to overcome this problem in an existing tube is to use a swamping resistor of such magnitude that the combined tube grid current plus resistor current is never negative or only slightly so.

In order to provide a constant amplitude pulse of long duration, it is common to select the operating point at a rather high tube drop. Discharge of the coupling condenser during the pulse would introduce droop. The output pulse may be kept constant in amplitude by increasing the grid

drive during the pulse such that the operating point on the characteristic curve shifts at the end of the pulse to a lower value of tube drop. In this way the output voltage pulse may be kept at constant amplitude. At the beginning of the pulse the load line may cross the negative grid current area, depending on how high an E_{bb} is chosen to make up for the increasing voltage drop in coupling condenser voltage during the pulse. If the load line passes through the negative grid current area, the drive voltage is not controlled by the driver and the resulting effects will depend on tube and circuit interaction. In general it is not possible to achieve stable operation in this area unless the rise time of the pulse is so short that the total negative charge removed from the grid by secondary emission is small enough not to affect the driving voltage.

Another type of instability in pulse amplitude is due to space charge neutralization by positive ions. This subject has been investigated by Hernqvist[18, 19]. It occurs in tetrodes, shielded-grid triodes and other multi-grid tubes, if the residual gas pressure in the tube is not low enough. When the peak pulse current has been established in the screen-grid anode region, there is a potential dip in this region due to the space charge. The electron current ionizes the residual gas, and the positively charged ions will collect in this negative potential well. These positive ions neutralize some of the negative space charge, which results in a more positive potential gradient at the grids. The net result is an increase in plate current and decrease in screen-grid current. In other words, the plate current is no longer limited to the value given in equation (5) since this equation assumes that only electrons are present in the grid-anode region. For short pulses this effect is not noticeable because of the slow mobility of the positive ions. In general the time of formation may vary from a half to several microseconds. The lower the plate tube drop at the operating point, the deeper the potential well becomes and the more likely one is to see this effect. Even if the resulting small step in the pulse is not objectionable, it is not apt to be stable for long periods of time. It can also produce parasitic oscillations. See Figure 17.

4. High Voltage Breakdown and Circuit Problems.

Internal flash arcs in power tubes date from the first use of high power communication transmitters at Rocky Point, Long Island. This phenomenon came to be known as the "Rocky Point" effect and has been discussed in various papers. Improved processing of tubes and better tube design have resulted in improved high voltage transmitter tube stability. The introduction of the energy diverter or crowbar, as well as other circuit improvements, has also resulted in substantial improvement in high voltage stability of power tubes. For example, with proper circuitry the ML-7560 running at its maximum rated 50 KV dc plate voltage and pulsing a klystron load will kick out so infrequently, i.e., once in many hundred hours, that it is difficult to tell whether the tube itself caused the kick out. This tube will operate
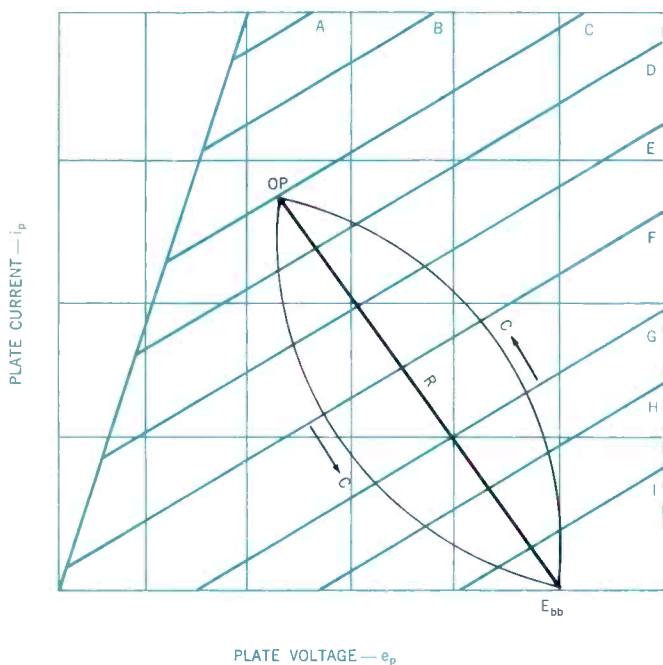

Figure 16 — Resistive and capacitive load lines on constant grid voltage characteristic curves.

quite stably for hours in oil at 65 KV dc, but the kick out rate has not been determined under such conditions.

The study of high vacuum insulation has been the subject of a great many papers[6, 20, 21, 22] but the cause of high voltage breakdown is not fully understood. It is a complex phenomenon involving several mechanisms. The gas level in a tube is only a secondary consideration in breakdown problems. Tubes have shown good stability with gas levels above 10^{-6} torr, whereas tubes of the same type have shown poor stability with gas level below 10^{-8} torr. At one time it was thought that high vacuum insulation would cure itself after an arc. This fact is only true if the energy dissipated in the vacuum arc is small enough. With high power and low source impedance rectifiers too much energy can be dissipated in a vacuum arc to permit self-healing. Such high power arcs will produce momentary high gas pressure and also vaporize metal from the electrodes in the tube. This vaporized metal will condense on the electrodes, and, since this material is loosely bound to the electrodes, it will act as emission points for additional vacuum arcs. If the energy dissipated in a tube exceeds a few joules, holes may be melted in grids or filaments with resulting catastrophic damage.

A similar situation results with sphere gaps in air. If a pair of sphere gaps has a megohm impedance in the lead to each ball, the sphere gap may be used as a voltage measuring device. If a large amount of energy is allowed to discharge between the balls of a sphere gap (series resistance in the leads very low), an appreciable etching or even surface melting of the balls will occur. Furthermore, the voltage breakdown between the balls will be lowered for subsequent arcs.

The use of a crowbar[23, 24, 25] which will act in less than 10 microseconds to divert the energy from a flash arcing tube to a shunt circuit has been of tremendous value in maintaining the high voltage stability of power tubes. This energy diverter must, in general, be a gaseous device such as an ignitron, thyratron or spark gap, so that its internal impedance can be low enough to transfer the arc from the power tube to the crowbar circuit. The diverter circuit must also be capable of dissipating the power fed through until the primary circuit is opened. It should be borne in mind that crowbars are essential for good high voltage tube stability even when flash arcs are too weak to cause catastrophic damage.

In high power pulsers flash arcing in tubes can be caused by over-volting induced by circuit malfunction. In general, a good crowbar circuit will protect the tube from such occasional irregularities. An understanding of the types of malfunction which can occur aids the circuit designer in producing a good, stable transmitter.

In the design of power triodes and tetrodes the vacuum insulation between the plate and the screen grid in tetrodes, or the plate and control grid in triodes, is one of the major considerations. For stable high voltage tube operation it is
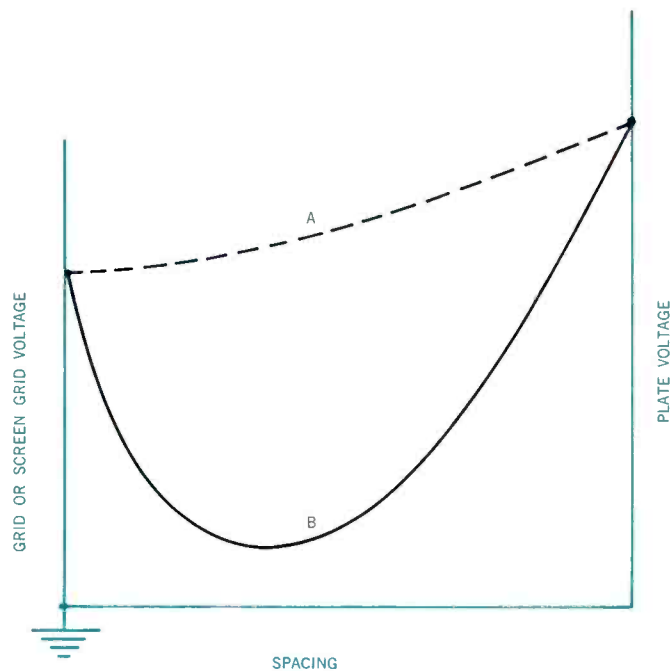

Figure 17 — Potential distribution between outer grid and anode; "A" for electrons in high vacuum, "B" for gas ionization neutralizing electron space charge.

necessary to have adequate spacing between these two surfaces, and the surfaces must be clean and smooth. Kilpatrick[6] has given a data for the maximum "spark free" potential differences between two electrodes in vacuum as a function of their spacing (Appendix II.) His curve assumes parallel plane electrodes, and therefore somewhat larger electrode spacing must be used in vacuum tubes such that the increased voltage gradient at the surface of the grid wires is taken into account.

It is to be noted that the field gradients permissible in vacuum devices of large electrode areas are from 50 to 100 times smaller than would be expected from true field emission theory. This difference is due to several causes which have not been independently evaluated. Some of the sources of voltage breakdown[6, 20, 21, 22] within the tube are foreign atoms which lead to low work function areas, whisker growth, Schottky effect on the grids, ion exchange phenomena, photoelectric effect, and charges on insulators. It was pointed out in the beginning of this article that determining the proper spacing between the outer grid and anode involves a compromise between tube efficiency or size and an ultra-conservative maximum plate voltage rating. See Figure 3 and equation (5). It is easily seen from equation (5) that as d is increased e_p must also be increased if e_g is fixed. This means that as the outer grid to anode spacing is increased in order to increase the plate voltage rating of a tube, the tube drop will be increased somewhat faster. The tube designer must, therefore, establish a grid-anode spacing which assures good high voltage stability; but he must not over-do this spacing, since it will reduce tube efficiency.

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Since the tube will necessarily be designed to be as efficient as possible, it is not feasible to have a large safety factor for plate voltage. Therefore, it is essential that circuit designers pay particular attention to the maximum voltage rating for the tube. If large transients must be expected, either a higher voltage tube should be selected or suitable protective devices should be incorporated to clip transients.

The most common sources of circuit induced high voltage instabilities are:

(1) Inductive effects in the discharge circuit of pulsers.
(2) Arcing in the load.
(3) Parasitic oscillations.
(4) Line voltage surges.

In high power pulser circuits, when the current pulse is reduced to zero at the end of the pulse period, a transient voltage will be developed at the tube anode which adds to the dc plate voltage. The magnitude of this pulse will depend on the total inductance in the load circuit, the rate at which the plate current is cut off, and the anode to ground capacitance. The obvious ways of minimizing this effect are (1) to use a clipper tube, (2) to reduce the inductance to a minimum, (3) to lower the di/dt, that is, take a longer fall time. Since $\frac{1}{2} LI^2$ is stored in the inductance of the load circuit during the pulse period, it will be necessary to dissipate this energy at the end of a pulse. In many applications, pulse switch tubes are used far below their anode dissipation capabilities, and hence, by using a slow fall time at the end of the pulse tail, this energy can be absorbed in the anode of the switch tube. If it is necessary to have a fast fall time, some other provision must be made to absorb this energy, such as by diode clippers.

In triodes there is an area in the static characteristics (Appendix III) where the grid current is actually negative or opposite to the normal electron current picked up by the grid during positive drive. This area of reverse grid current, which is due to secondary grid emission, normally does not cause much trouble in the operation of the tube, since the load line either does not pass through this region, or the rate of rise and fall of the grid voltage is fast enough such that the inductance in the grid circuit assures stable operation. However, when the load shorts (arcs during a pulse), the grid drive on the switch tube is at maximum value, and the plate voltage on the tube suddenly approaches or exceeds the dc power supply voltage. See horizontal dotted line in (Appendix III). Under such conditions one can get what is commonly known as "pulse stretching." Due to secondary emission, the grid driver loses control of the grid potential. This results in the grid rising toward anode potential, and one of two things can happen:

(1) The grid voltage may get so high as to cause a breakdown between grid and cathode. This will cause a sudden reduction in plate current, which will produce a high peak anode voltage which often results in a breakdown over the outside of the tube before a vacuum breakdown occurs.

(2) The grid will become so positive that the secondary emission ratio of the grid becomes less than one, and the grid regains control, reducing the plate current to zero. di_p/dt may become large, and a high transient plate voltage results. A tube breakdown may then occur, or the tube may be stable after having passed a lengthened pulse.

Plate voltages have been viewed with an oscilloscope which are from two to two and a half times the dc plate voltage when the load device arcs. Similar effects happen with tetrodes when the load device arcs. Theoretically the screen grid by-pass condenser would be able to prevent the screen grid from losing control, except for the inductance in the screen grid circuit. Since these transients occur in times usually less than a microsecond, a very low lead inductance is essential to maintain control of the screen grid when a load arcs. Of course, even if the screen grid does not lose control, the $\frac{1}{2} LI^2$ in the shorted load shows up as excessive anode voltage unless some other sink is provided to absorb this energy.

One means of protecting the switch tube from such transients is to clamp the control grid back to bias whenever the load arcs. Of course one has to take care that the plate current is not cut off too abruptly, otherwise a high transient plate voltage will show up. A thyratron in the switch tube grid circuit covered by U. S. Patent 3,069,548, and shown in Figure 18, with a proper rc time constant, has been demonstrated to be capable of shutting off switch tubes without causing excessive anode voltages. In fact, with this circuit it is possible to shut off the switch tube without using the crowbar to short the plate power supply when the load device fails.

Power tubes used in CW power amplifiers or oscillators will also be subject to high voltage transients and subsequent loss of vacuum insulation when arcs in the output circuit occur. Although 30 kV/cm is considered to be the dielectric strength of air for parallel plane electrodes, a large safety factor must be used. High voltage circuit components collect dust, oxidize and otherwise become contaminated such that breakdowns can occur at field gradients of a few kV/cm.

Parasitic oscillations can also induce over-volting of circuit components with resultant application of high transient voltages at the tube electrodes. Oscillations of this type are due to energy coupled from some part of the output circuit to an input circuit. The only way of preventing parasitic oscillations is to locate the circuits causing the trouble and provide damping (i.e., lower the Q) or alter the phase and/or amplitude of the feedback such that oscillations are not self-sustaining. Pretesting a circuit with a resistance load minimizes many of the causes of circuit instabilities. Final "de-bugging" with the actual load is essential. Tetrode tubes with their higher gain and low grid drive are more susceptible to oscillation problems than triodes. A suitable electrostatic shield between input and output circuits is highly desirable.
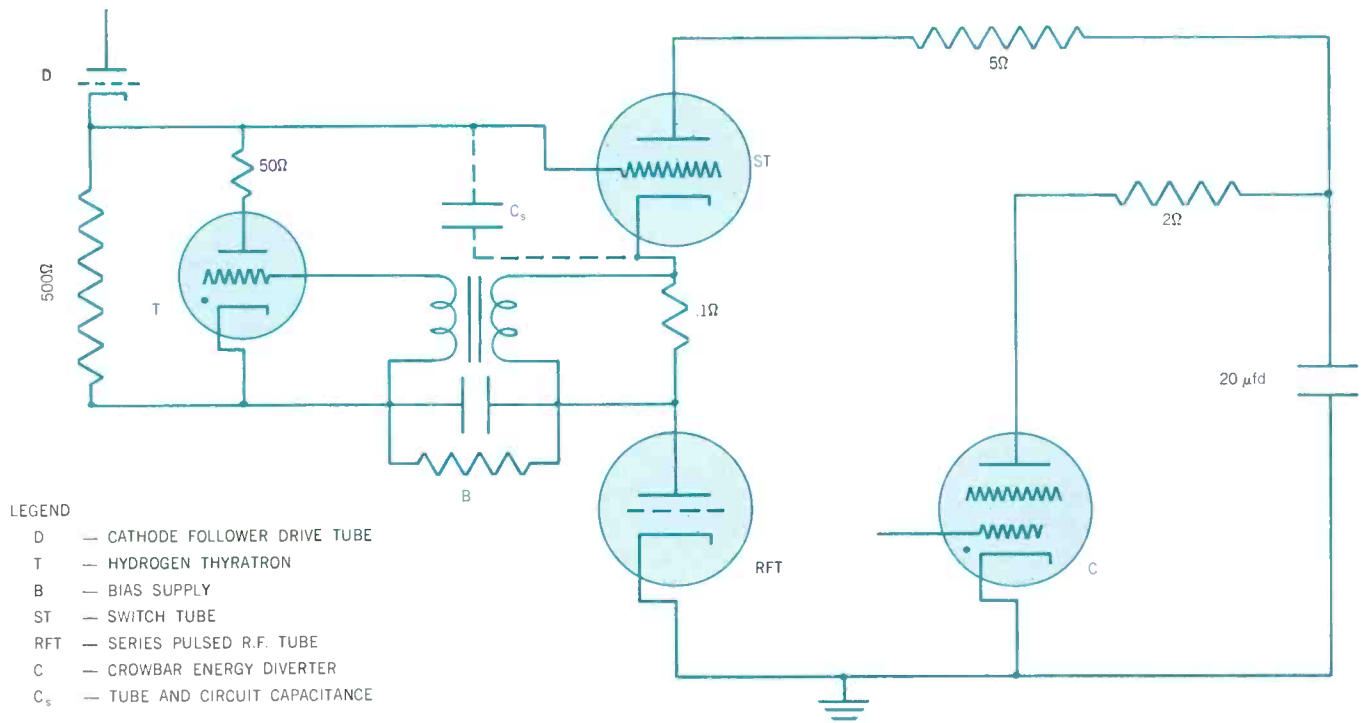
Figure 18 — Circuit showing a thyratron in a switch tube grid circuit. The switch tube is cut off when load tube arcs by firing the thyratron, T, by a voltage developed across 0.1 ohm resistor.

LEGEND

D — CATHODE FOLLOWER DRIVE TUBE
T — HYDROGEN THYRATRON
B — BIAS SUPPLY
ST — SWITCH TUBE
RFT — SERIES PULSED R.F. TUBE
C — CROWBAR ENERGY DIVERTER
C_s — TUBE AND CIRCUIT CAPACITANCE

Barkenhausen-Kurz[26] type of oscillations can be a cause of trouble whenever a triode or tetrode is over driven, i.e., driven close to or beyond the diode line. Figure 19 shows the static data for a high-voltage tetrode using lines of constant grid drive voltage. It is to be noted that at low plate voltage, i.e., to the left of the line marked $i = K e_p^{3/2}$, the current from the cathode due to the grid drive and screen grid voltage of 1000 volts cannot arrive at the plate but ends up on the screen grid or control grid. Equation (5) gives the maximum current which can arrive at the anode for a given plate and screen grid voltage. With the latter fixed, the current to the plate must decrease as the plate voltage is decreased. Actually a virtual cathode is formed between the screen grid and anode. Electrons passing the screen grid return to the screen grid and may oscillate about the screen grid several times before being collected by the screen grid. This oscillation is a transit time type of oscillation and is a function of tube geometry and applied voltages. Its amplitude and frequency are affected by the external tube circuitry. The power involved is usually quite small, but it may be enough to cause trouble, particularly if other circuitry is resonant at the same frequency. The practice of applying full drive power and then raising the anode voltage is conducive to troubles of this sort, since one runs through the complete gamut of plate and grid voltages in the Barkenhausen-Kurz region.

Line voltage surges can occur due to various causes. In induction and dielectric heating equipment where filter chokes and condensers are often omitted, a starting transient of nearly double the dc power supply voltage can occur if the full plate voltage is applied by the snap of a switch. The magnitude of the over-voltage depends on the instantaneous phase of the line voltage at the time the primary contacts are closed and also on the loading of the oscillator. To control starting transients, a load on the secondary of the transformer which opens in a few seconds after closing the primary contactor is usually sufficient.

In power amplifiers or pulsers using well filtered power supplies, there should be no such transients. At high power levels it is advisable to use induction regulators so that the voltage may be raised slowly from half to full power. If voltage must be snapped on instantaneously, it is advisable to provide half-voltage taps so that a new tube can be run for a while at reduced voltage and power. Similarly, a dropping resistor in the line that will permit coming on at 80%-90% of plate voltage is very helpful in aging a new tube. This resistance can be shorted out after a few minutes to provide full power.

It has been shown that a few joules can cause permanent tube damage. Contrary-wise, 500-1000 joules may cause no permanent damage. When a tube is over-volted, it is difficult to predict the course of an arc. Either sufficient series re-
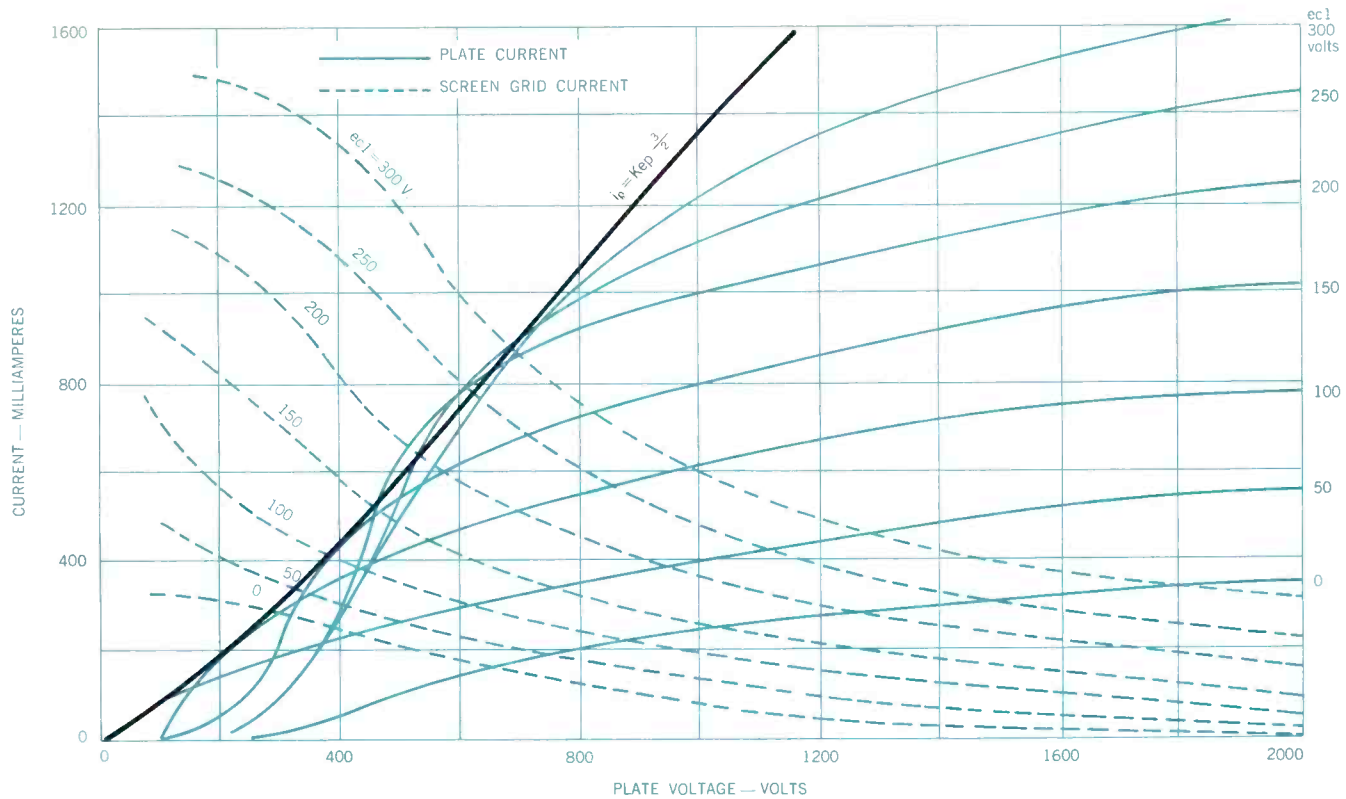
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Figure 19 — Typical Constant Grid Voltage Characteristics for tetrode ML-7248. Line labeled $i_p = k_{ep}{}^{3/2}$ shows plate current drawn from virtual cathode between screen grid and plate (Equation 6).

sistance must be included in the plate supply lead or a crowbar must be used, or both. At power levels above 100 KW it is essential to use fast crowbars[23, 24, 25] to divert the stored energy in the circuit from discharging through the power or switch tube. It is also necessary to use fast circuit-breakers, since once the crowbar fires, energy will be fed in from the lines until the primary contactor is opened. The design of the crowbar circuitry must be such that the discharge circuit through the crowbar is critically damped. If the inductance in the crowbar discharge circuit resonates with the filter capacitor, and the losses in the circuit are small, the stored energy will not be dissipated, but the charge on the condenser will be reversed. The power tube may then dump this energy with damage to itself.

In addition to using a critically damped crowbar circuit, some protection is necessary to make sure that the filter condenser does not recharge again after the condenser has been dumped and the crowbar de-ionizes. In other words, it may be necessary to fire the crowbar several times until the main contactor is open.

In one 200 KW output dielectric heating equipment where a tube was arcing several times a day, the installation of a crowbar circuit allowed the same tube to operate for over two months before a kickout occurred. In this case, the energy dumped in the tube prior to installation of a crowbar was enough to vaporize metal within the tube,

causing high susceptivity to additional flash arcing; but, there was not enough energy to cause permanent or catastrophic tube damage. The installation of the crowbar circuits kept the dissipated energy in the power tube low enough to allow the tube to remain stable.

Flash arcing in tubes with ratings of less than 100 kVdc should not be a major cause of voltage instability. Properly designed tubes used in circuits with adequate protective devices should not break down under voltage of their own accord. When new tubes are installed in a circuit for the first time, some seasoning can be expected, but in general the tubes should run stably after the first few hours of operation. There are so few equipments in the field today using tubes with voltage ratings above 100 kVdc that it is not possible to say whether long stable operation can be expected at high voltages or whether some new phenomena may appear.

5. Voltage Breakdown Outside of the Tube.

In the early days of pulse modulator equipment design, it was discovered that many radiation cooled tubes with long glass envelopes could withstand plate voltages several times the dc ratings given for CW oscillator or amplifier operation. Of course the peak plate voltage rating on all tubes used for CW rf applications is twice the dc power supply value, and therefore power tubes can be operated as pulse switch tubes

at twice the dc ratings given for Class C rf oscillator or amplifier applications. The ratings for plate modulated rf power tubes are such that the peak of the rf voltage is nearly four times the dc plate voltage rating. It is usually reasonable to assume that the peak plate voltage due to backswing in pulse modulator applications can equal the peak rf plate voltage which would be encountered in case of rf applications with plate modulation. In this case the dc modulator tube rating would be about three and one-half times the dc plate voltage for the plate-modulated rf application. Although some of the older style radiation cooled tubes when used as switch tubes ran a factor of two higher than $3\frac{1}{2}$ times the dc plate modulated ratings, the same result is usually not possible with external copper anode power tubes because in the latter case the glass envelope is not long enough even if the internal vacuum spacing is adequate. Some power tubes, if immersed in oil, sulpher-hexafluoride or pressurized air, can be run at plate voltages considerably higher than inferred from the above discussion. Operation of commercial tubes at such high values of plate voltage will necessitate some high voltage aging at 15 to 20 per cent above the desired operating level. Furthermore, the user of such tubes will have no assurance that the manufacturer will continue to make tubes which will work in his circuit, since the manufacturer may not be checking such a high voltage characteristic. The user should obtain a firm rating from the manufacturer to be sure that future tubes will continue to do the same job.

As can be seen from the above comments, ionization of the air outside the tube limits the maximum usable plate voltage. Such ionization will lead to arcing over the tube envelope with danger of puncturing the glass or ceramic envelope. Conversely, if a tube normally runs satisfactorily within its maximum ratings and occasionally arcs over externally, it is proof that the plate or grid voltage rating has been exceeded due to some voltage transient. It is mandatory to keep envelope insulation clean. Dirty air or a collection of electrically precipitated dust on the tube envelope will lower the hold-off capability of the tube by a factor of two or more. For economy of space and to simplify problems of cleanliness, it is advisable to use oil or enclosed gas insulation above the 50 kilovolt level.

For operation of tubes in air at voltages above 10 kilovolts, the use of corona rings suitably disposed can improve the maximum rating of the tube and also offer protection against catastrophic failures. Properly designed corona rings reduce the maximum electric field gradient in the air outside the tube. Without corona rings the maximum electric gradient usually occurs at the metal-insulator joint. The corona rings should be designed such that in the event of transient over-volting, the maximum gradient occurs at the surface of these rings and then the flashover should occur in the space between the rings instead of over the tube envelope. It has also been shown that a blower driving air over the envelope seems to remove ions as they form and thereby substantially improving voltage stability. "Corona rings" are also useful under oil to reduce the electric field at the envelope seals and the probability of envelope puncture.

6. Effects of Alternating Voltage Heating of the Cathode.

Most thoriated-tungsten cathodes are composed of wires. If these cathodes are heated by alternating current, an alternating magnetic field exists around the filament wires and extends into the grid-cathode space. It has been shown by Hardie[27] that this time-varying magnetic field has an influence on the characteristic curves, particularly at low grid-drive voltages when the electron velocity in the grid-cathode space is low. At full grid drive and maximum cathode current density, the effect is small. It may be necessary to use dc cathode heating if extremely flat-topped pulses are required. When dc cathode heating is used and long tube life is desired, it may be necessary to change polarity of the heater terminals every thousand hours or so. The advisability of changing polarity is determined by the ratio of average plate current to the filament heating current. If the average plate current is less than 1% of the filament heating current, it will not be necessary to change polarity. The problem here is due to the added heating on that end of the filament wire which carries the average plate current as well as filament heating current. The criterion of 1% says that the added wattage on this end of the wire is 2%. If this figure is allowed to go to a 5% increase in wattage, the emission life of these filament legs will be halved.

Another effect of alternating voltages on cathodes is the volt drop from one end of the cathode to the other. For all cathodes except those that are indirectly heated (radiation heated or bombarded cathodes), the effective grid-cathode driving voltage varies due to the difference in true grid driving voltage from one end of the cathode to the other. For example, if the rated heater voltage is ten volts and one side of the cathode is at ground potential, the grid voltage with respect to the grounded end of the cathode is simply e_g, the applied grid voltage. The driving voltage at the other end of the cathode will assume all voltages in the range of $e_g \pm 14.1$ volts in the course of one cycle of the heater voltage. If this much uncertainty in the grid drive voltage is critical in an application, then dc filament excitation may be required. A center tapped resistor across the filament terminals which draws about 5% of the normal cathode heating current will considerably reduce ripple due to this cause.

7. Application of Tubes in Parallel or Series.

Hard tube switches may be used at full ratings in either parallel or series operation, or both, but it is necessary to derate tubes on both voltage and current unless one is prepared to make rather extensive adjustments periodically and whenever tubes are changed. At a fixed grid drive and fixed tube drop (plate voltage), the plate current may vary from tube to tube by as much as 10% for tubes with thoriated-tungsten cathodes and even more for oxide cathode tubes

due, in the latter case, to the slow deterioration of oxide cathodes during life. If two tubes are used in parallel and only total or average current is monitored, one tube may be running at excessive plate current. If tubes are operated close to or below the knee of the plate current curve on the constant grid drive characteristics, the situation may be considerably worse. When tubes are used in parallel, maximum cathode current and grid dissipation ratings should be reduced by 5 to 10%.

Tubes in parallel may find themselves opportunely situated to oscillate in a push-pull mode at some frequency determined by the circuits composed of plate leads, stray capacitances, etc. Usually a non-inductive resistor in individual grid and plate leads suffices to lower circuit Q's to a value which prevents oscillation. It is also possible to determine the critical circuits and adjust the feedback such that the phase of the fed-back energy is improper to support oscillations. Multiple-tube pulse modulators have proven much simpler as regards suppression of parasitic oscillations compared with rf amplifiers or oscillators.

When tubes are used in series, the primary problem is to see that plate voltage ratings are not exceeded. If one tube is switched on before the second tube, the full voltage will appear across the non-conducting tube. It is not necessary to have the rate of rise of the grid drives identical, since the voltages across the tubes need not be balanced, and any current through the load subtracts from the total instantaneous tube voltages. At the end of the pulse, the time constant for the plate circuits of the two individual tubes must be reasonably matched so that the voltage across either tube never exceeds the individual tube rating. Here again circuit details are much less critical if tubes are at 80 to 85 per cent of their maximum plate voltage ratings. Since tubes passing the same current in series will have different tube drops, depending on variations in characteristic curves and also variations in drive voltage, maximum grid and plate dissipations should be lowered by about 10 per cent. Exact values for derating should be worked out in each individual case, depending on the particular circuits used and the tolerances allowed on circuit elements and on voltage regulation.

In balancing voltages and time constants, it should be remembered that the capacitance data on tube data sheets are only the interelectrode capacitances considering that the tube is far removed from other circuit elements and the grounded cabinet walls. The tube manufacturer cannot give more detail since he does not know in what environmental conditions the tube may be situated. It is necessary to open conductive leads and measure actual capacitances with the tube in place.

One item which is often overlooked when operating tubes in series is due to the fact that electrostatic fields add. Consider two tubes connected in series as shown in Figure 20. Each tube has 50 kv from plate to cathode when both tubes are non-conducting. Nevertheless, tube A has capacitance

to the grounded case and the difference of potential here is 100 kv. Under these conditions the electric field gradients at the glass-metal seals of tube A may be considerably greater than those of tube B. This situation may cause corona at the plate seal of tube A and may even increase the voltage gradient inside the vacuum envelope of tube A. The latter effect can happen if the electrostatic field due to the difference of plate voltage from the plate of tube A to ground reaches through the glass tube envelope to the internal tube electrodes. Such an effect is particularly likely with tubes using large glass bulbs and radiation cooled anodes. Tube A may be protected from such stray electrostatic fields by surrounding the cathode-grid structure with an electrostatic shield as indicated by the dotted lines in Figure 20.

In series operation of tubes particular care must be taken to keep lead inductance to an absolute minimum. Large diameter coaxial connections are advisable. Otherwise, very large transient voltages may build up due to lead inductance and high rates of change of current, particularly under fault conditions when extremely high di/dt can occur. Great long arcs will fly in all directions. For the same reason tubes with large internal cylindrical leads to all electrodes will be much freer of flash-arc damage than tubes with straps connected from tube terminals to the active electrodes.
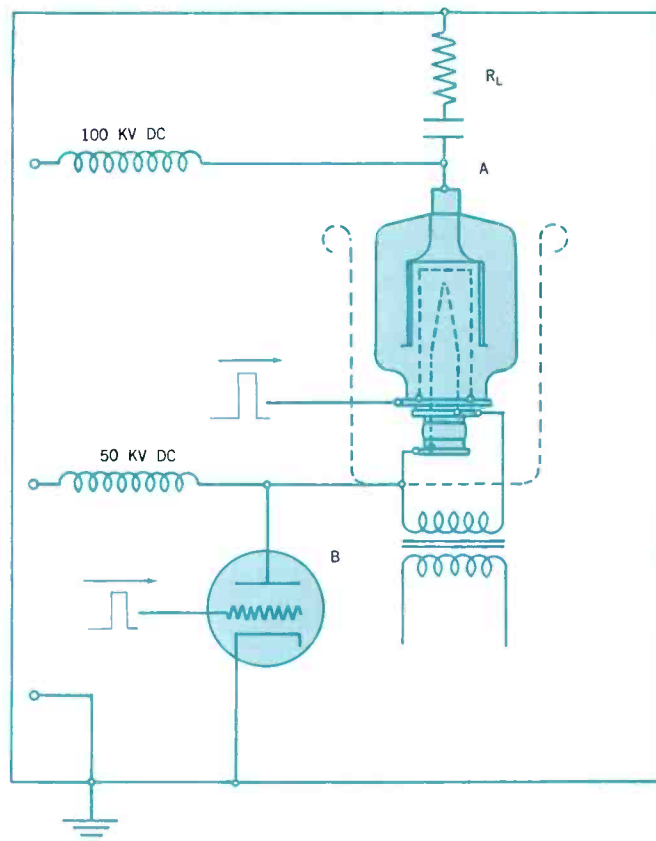

Figure 20 — Circuit for tubes in series. Dotted line shows position of electrostatic shield so that tube "A" never "sees" more than rated 50 kv.

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Appendix I

Switching Power of Machlett Pulse Tubes

Switching power of the current line of Machlett pulse tubes is indicated below. Each tube will deliver output current and voltage approximately up to values indicated by either an 0 or a +.
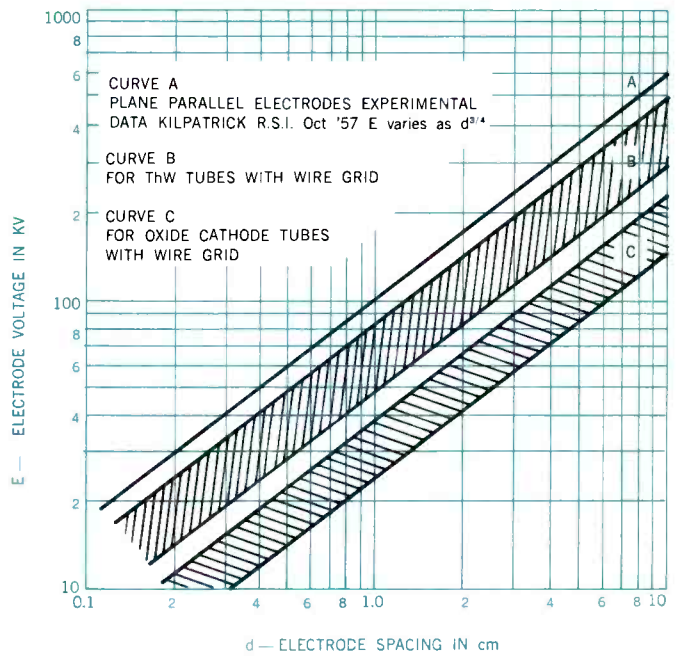
Lines of constant switching power through these coordinates show the range of current and voltage possible by the use of an output pulse transformer.
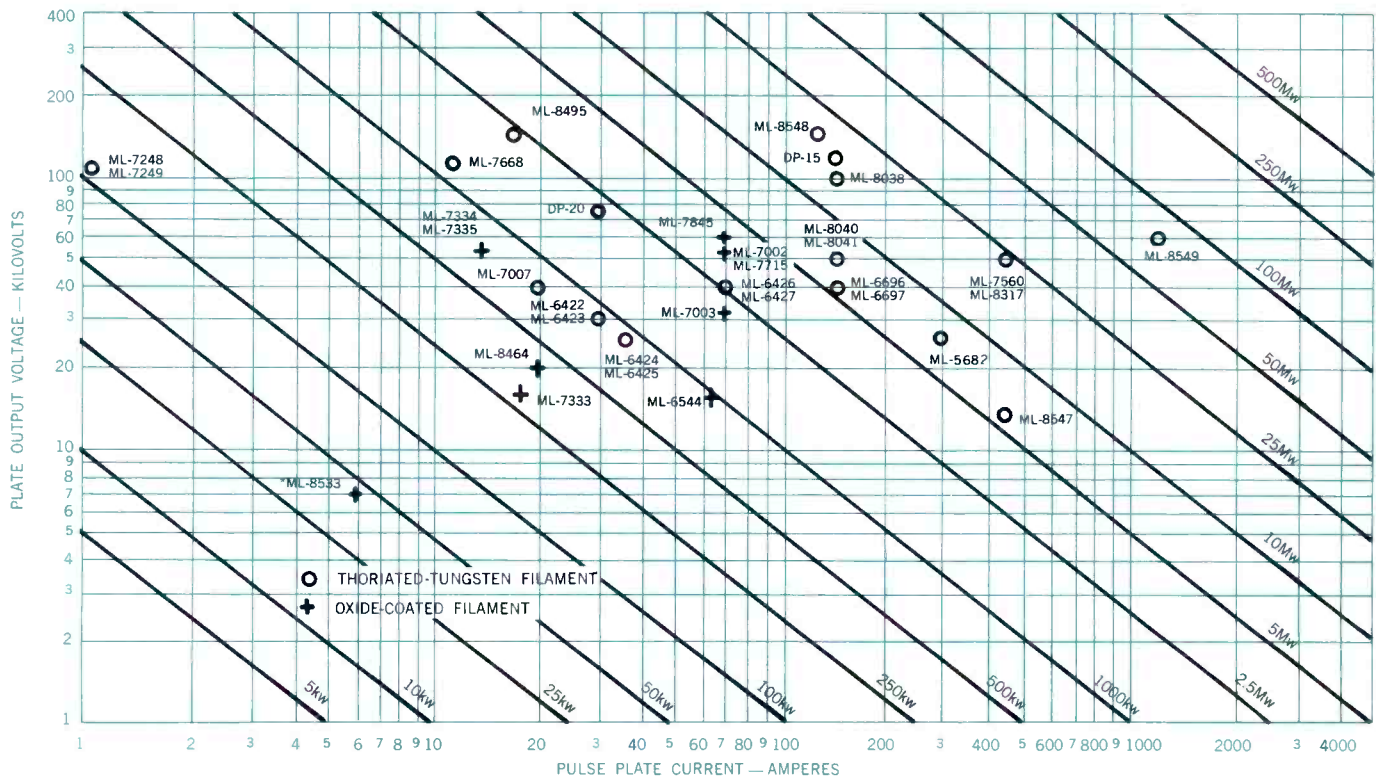
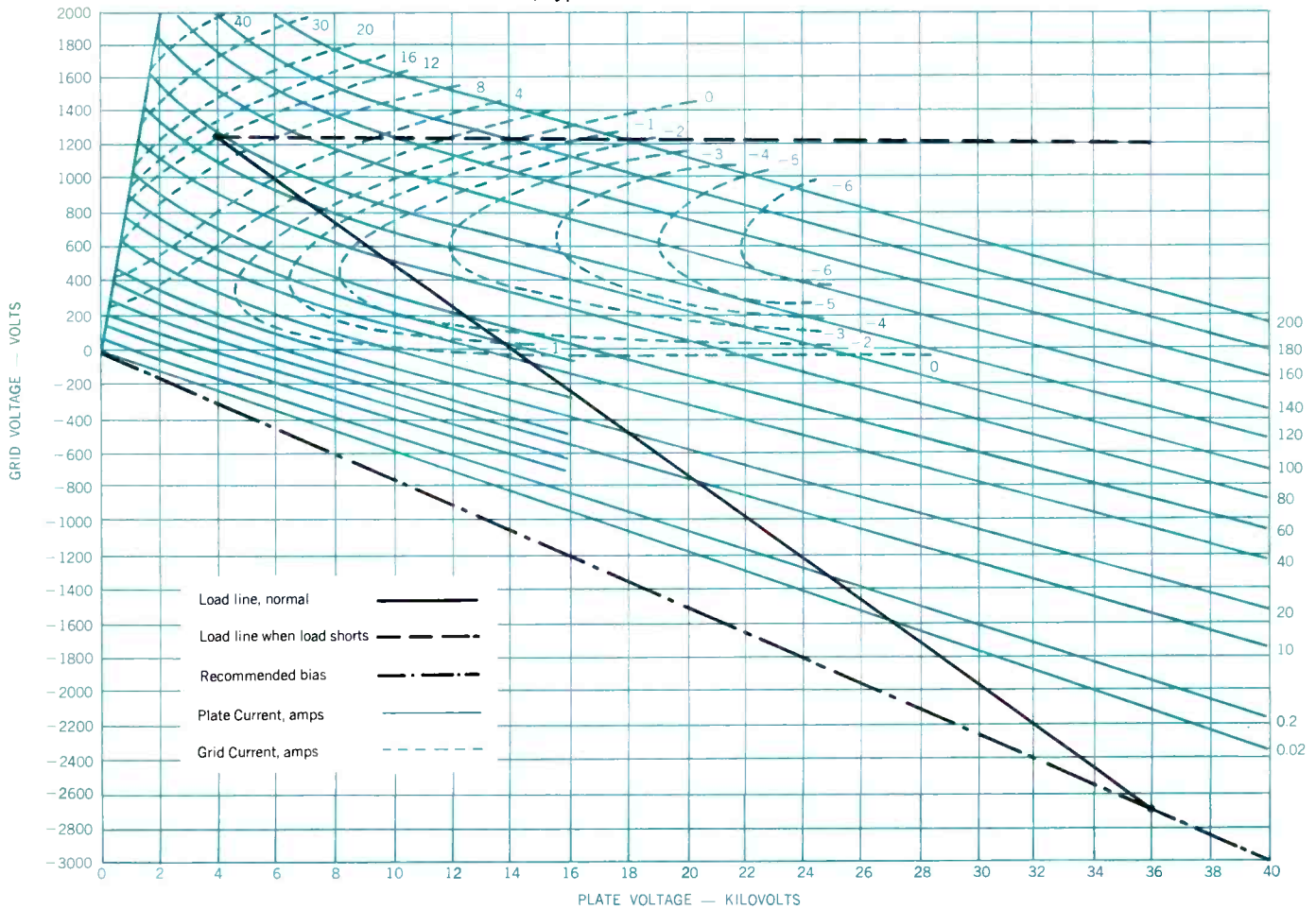*UHF TRIODE. For data on other tubes of this type, Consult MACHLETT Engineering Department

Appendix II

Anode Voltage Rating versus Outer Grid to Anode Spacing.

CURVE A
PLANE PARALLEL ELECTRODES EXPERIMENTAL
DATA KILPATRICK R.S.I. Oct '57 E varies as d^(3/4)

CURVE B
FOR ThW TUBES WITH WIRE GRID

CURVE C
FOR OXIDE CATHODE TUBES
WITH WIRE GRID

E — ELECTRODE VOLTAGE IN KV

d — ELECTRODE SPACING IN cm

Appendix III

ML-6696 Constant Current Characteristic Curves showing Reverse Grid Current
Area, recommended dc bias, typical Load Line and Load Line when load shorts.

GRID VOLTAGE — VOLTS

Load line, normal
Load line when load shorts
Recommended bias
Plate Current, amps
Grid Current, amps

PLATE VOLTAGE — KILOVOLTS

ML-8549*
Super Power Triode

High Duty
Pulse Power
to 60 Mw

Description:

The ML-8549 is a super-power general-purpose water-cooled triode featuring extremely favorable plate-grid current division which results in minimum drive-power requirements. The cathode of this tube consists of sturdy self-supporting thoriated-tungsten filaments. The coaxial terminals have low inductance and high heat-dissipation capability. Insulating members are low-loss ceramic.

When used as a switch tube in hard-tube pulse modulators for radar or similar applications, it can deliver more than 60 Mw pulse output with pulse widths up to 10,000 microseconds at a duty factor of .06. When used as a pulsed rf amplifier operating at frequencies up to 30 Mc, the ML-8549 is capable of delivering 10 Mw, also at long pulse duration and high duty factors. When used as a pulsed modulator, a maximum plate voltage of 65 kVdc applies.

When operating as a Class C amplifier or oscillator at frequencies up to 30 Mc, the ML-8549 is capable of a continuous output in excess of 2.0 MW. The maximum CW plate voltage rating of 25 kVdc applies at frequencies up to 30 Mc.

The water-cooled anode of the ML-8549 is capable of dissipating up to 500 kW. The tube can be operated in air at maximum plate voltage ratings. The ML-8549 is supplied with an ion pump for maintaining a high vacuum during operation.

MAXIMUM RATINGS AND TYPICAL OPERATING CONDITIONS

Pulse Modulator or Pulse Amplifier

Maximum Ratings, Absolute Values

DC Plate Voltage	65	kV
Peak Plate Voltage	70	kv
DC Grid Voltage	−5000	V
Peak Negative Grid Voltage	−6000	v
Pulse Cathode Current	1200	a
Grid Dissipation	9	kW
Plate Dissipation	500	kW
Pulse Duration	10	ms
Duty Factor	.06	

Typical Operation

DC Plate Voltage	65	kV
DC Grid Voltage	−4000	V
Pulse Positive Grid Voltage	3000	v
Pulse Plate Current	1100	a
Pulse Grid Current	10	a
Pulse Driving Power	70	kw
Pulse Power Output	65	Mw
Pulse Plate Output Voltage	59	kv

Plate-Pulsed RF Power Amplifier and Oscillator
Class C

Maximum Ratings, Absolute Values

Peak Plate Pulse Supply Voltage	40	kv
DC Grid Voltage	−4000	V
Pulse Cathode Current	1200	a
Grid Dissipation	9	kW
Plate Dissipation	500	kW
Pulse Duration	10	ms
Duty Factor	.06	

Typical Operation	Cathode Drive	Grid Drive	
Peak Plate Pulse Supply Voltage	38	38	kv
DC Grid Voltage	−2300	−2300	V
Peak RF Grid Voltage	5500	5500	v
Peak RF Plate Voltage	32	32	kv
Peak Plate Current from Pulse Supply	400	400	a
Peak RF Fundamental Plate Current	630	630	a
Peak Plate Dissipation	5.2	5.2	Mw
Plate Dissipation at .01 Duty	52	52	kW
Peak Driving Power	1750	33	kw
Peak Grid Dissipation	24	24	kw
RF Load Resistance	60	51	ohms
Peak Power Output	11.8‡	10	Mw

Developments

ML-8545 }
ML-8546 }   **

ML-8545   Vapor-Cooled Tetrode
ML-8546   Water-Cooled Tetrode
CW power to 330kW

Description:

The ML-8545 is a general-purpose vapor-cooled tetrode capable of 300 kW continuous output as a Class C amplifier or oscillator at frequencies up to 30 Mc.

The anode is designed to dissipate 150 kW during continuous operation and substantially higher power during momentary overloads or intermittent operation. Coaxial grid and cathode mounting structures provide low-inductance, high-dissipation rf terminals. The cathode consists of sturdy thoriated-tungsten filaments. Low-loss alumina ceramics are used for all insulation members.

Maximum ratings apply at frequencies up to 30 Mc. Useful power output can be obtained at higher frequencies with an appropriate reduction in ratings.

The ML-8546 is a water-cooled version of the ML-8545. The anode is designed to dissipate 125 kW.

MAXIMUM RATINGS AND TYPICAL OPERATING CONDITIONS
(Continuous Commercial Service)

RF Power Amplifier or Oscillator
Class C Telegraphy

(Key-down Condition per Tube
Without Amplitude Modulation)

Maximum Ratings, Absolute Values

DC Plate Voltage	18000	Vdc
DC Screen-Grid (No. 2) Voltage	2500	Vdc
DC Control-Grid (No. 1) Voltage	−1200	Vdc
DC Plate Current	23	Adc
Screen-Grid Dissipation	3000	W
Control-Grid Dissipation	1000	W
Plate Input	420	kW
Plate Dissipation	150	kW

Typical Operation, Grid-Drive Circuit

DC Plate Voltage	16000	18000	Vdc
DC Screen-Grid Voltage	1500	1500	Vdc
DC Control-Grid Voltage	−850	−950	Vdc
Peak RF Grid Voltage	1060	1200	v
DC Plate Current	21	23	Adc
DC Screen-Grid Current	1.7	1.8	Adc
DC Control-Grid Current	.1	.3	Adc
Driving Power, approximate	100	350	W
Plate Output Power	250	330	kW
Plate Dissipation	85	90	kW

Plate-Modulated RF Power Amplifier
Class C Telephony

Carrier Condition Except Where Noted For Use
With a Maximum Modulation Factor of 1.0

Maximum Ratings, Absolute Values

DC Plate Voltage	13000	Vdc
DC Screen-Grid Voltage	2000	Vdc
DC Control-Grid Voltage	−1200	Vdc
DC Plate Current	23	Adc
Screen-Grid Dissipation	3000	W
Control-Grid Dissipation	1000	W
Plate Dissipation	100	kW

Typical Operation, Grid-Drive Circuit

DC Plate Voltage	11000	13000	Vdc
DC Screen-Grid Voltage	750	750	Vdc
Peak AF Screen-Grid Voltage for 100% Modulation	750	750	v
DC Control-Grid Voltage	−500	−500	Vdc
Peak RF Grid Voltage	820	850	v
DC Plate Current	18	19	Adc
DC Screen-Grid Current	3.3	3.8	Adc
DC Control-Grid Current	2.3	2.8	Adc
Driving Power, approximate	1800	2200	W
Plate Output Power	135	180	kW
Plate Dissipation	60	70	kW

Note: Data contained on page 42 are based on initial design and test criteria. Before using these data in final equipment designs, consult Machlett for possible revisions.
**Proposed Technical Objective — Engineering Design Information.*

About the Authors

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Dr. Doolittle is Manager of Technology of The Machlett Laboratories, Inc., and has been responsible for the development of UHF and high power triodes and tetrodes as well as research on cathodes and allied subjects. He is also responsible for over-all scientific work of the engineering staff with particular emphasis on new products and processes. Dr. Doolittle is a fellow of the American Physical Society, and a Member of IEEE and the Electrochemical Society.

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Mr. C. F. Eggert received his BSEE degree from the State University of Iowa. Active in the technical communications field since 1955, Mr. Eggert has been an engineering writer, a publication engineer, and technical publications section supervisor. In his current position with Collins Radio Company, he is responsible for the preparation and publication of all technical information for the Collins airline communication and navigation product line. He prepared the maintenance and instruction manuals for the first Collins Distance Measuring Equipment (DME) used by commercial airlines.

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Mr. Henry Eggerding is a Senior Project Engineer with ITT Federal Laboratories in Nutley, New Jersey. He has been a leading member of that company's pioneering team which introduced crystal control to the 1000 mc band in 1945. Since then he has contributed to the design of the numerous pulse transmitters for DME, TACAN, and IFF. More recently he has been active in the 4 gc altimeter field.

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Mr. Richard W. Donovan received a B.S. in Electrical Engineering at the University of Kansas in 1957 and has performed graduate work in servomechanisms, transistor engineering, advanced mathematics and nuclear engineering. His special field includes pulse techniques, VHF transmitter and receiver design, microwave cavity design, microwave strip line design, UHF measurements and general electronic circuit design. He has responsibility for airborne DME and TACAN designs.

Most recent experience at Wilcox has been that of Project Group leader for the development of the Wilcox Model 814B General Aviation Transponder, Model 833 Distance Measuring Equipment, Model 914 Airline ATC Transponder and the Military 914X SIF System development sponsored by Wilcox, and the AN/PPN-16 X-Band Radar Beacon.

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